POLLUTION PREVENTION PROCESS INFLUENCES IN THE WEAPON SYSTEM ACQUISITION LIFE CYCLE

THESIS

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AFIT/GEE/ENV/97D-09

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AFIT/GEE/ENV/97D-07

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List of Acronyms

ASC	Aeronautical Systems Center
AFMC	Air Force Materiel Command
CE	Concept Exploration
DoD	Department of Defense
EMD	Engineering and Manufacturing Development
EPA	Environmental Protection Agency
ESH	Environmental Safety and Health
ESOH	Environmental Safety and Occupational Health
EVMS	Earned Value Management System
LCC	Life Cycle Cost
MAA	Mission Area Analysis
NEPA	National Environmental Policy Act
PDRR	Program Definition & Risk Reduction
PPE	Personal Protective Equipment
R&D	Research and Development
RCRA	Resource Conservation and Recovery Act
SPO	System Program Office
TASC	The Analytical Science Corporation
TPIPT	Technical Planning Integrated Product Team

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Abstract

This research develops a system structure for the pollution prevention acquisition process and uses system dynamics modeling to develop management strategies that optimize life cycle cost. The structure of the pollution prevention acquisition process is developed by identifying primary influences and mechanisms and determining how they interact within the acquisition process.

The model structure is based on the premise that rising total projected Life Cycle Cost (LCC) provides an incentive to perform pollution prevention changes to reduce the overall LCC cost. The model successfully produces the expected reasonable behavior, and confidence in the model structure is achieved using standard system dynamics verification testing.

In the model, laws and regulations appear to have the greatest impact on reducing overall LCC; however, this is driven by the high effectiveness values assigned in the model, which assume the ability of laws and regulations to directly address material substitution in the specified weapon system. Air Force Policies and financial incentives (the projected LCC exceeding the LCC goal) also have significant effects on reducing overall LCC. Further defining these parameters to accurately affect the appropriate degree of influence in the model structure is an integral part of developing an effective pollution prevention management strategy.

POLLUTION PREVENTION PROCESS INFLUENCES IN THE WEAPON SYSTEM ACQUISITION LIFE CYCLE

1. Introduction

Background

Currently, acquisition program budgets in the Air Force are shrinking and personnel levels are being reduced to align with a new post Cold War Air Force mission. Under these conditions, program managers are constantly asked to do more with less money and human resources. Efficient execution of program acquisition is a necessity, as program managers continually look for ways to reduce overall costs to their programs to help stretch scarce budget dollars. One possible avenue of reducing life cycle program costs is the implementation of a pollution prevention program.

According to the Environmental Protection Agency (EPA), the Pollution Prevention Act of 1990 defines pollution prevention as:

> Any practice which reduces the amount of any hazardous substance, pollutant, or contamination entering the waste stream or otherwise released to the environment (including fugitive emissions) prior to recycling, treatment, or disposal; and reduces the hazards to public health and the environment associated with the release of such substances, pollutants, or contaminants. (EPA, 1994:2)

Pollution prevention programs are favorable because by reducing hazardous substances, pollutants, and contaminants, they conserve raw materials and energy, reduce wastes, and lower hazardous material management and disposal costs. The reduction in the amount of hazardous materials also lowers the risk of criminal and civil

liability and protects public health and the environment (EPA, 1994:2). In addition to offering the potential cost savings listed above, pollution prevention efforts are also of interest to U.S Air Force weapon system program managers because the Federal Facility Compliance Act amendment to Resource Conservation and Recover Act (RCRA) waives sovereign immunity for the Department of Defense (DoD). This means government program and facility managers are now held equally accountable for environmental compliance issues just like their counterparts in industry.

Pollution Prevention efforts initiated by the Pollution Prevention Act are implemented in the Air Force through Federal Laws and Executive Orders, DoD Directives and Guidance, and US Air Force Directives, Guidance, and Instructions. At the Air Force level, the guidance concentrates more on specific items or lists such as Ozone Depleting Substances, the EPA List of 17 Toxic Substances, and other specific materials listed in the 40th Code of Federal Regulations (AFMC, 1996b:1-4). Individual program offices and depots are directed to review their technical documents, identify which of the hazardous materials listed are used in the weapon system, and then use their individual program funds to find substitutes for these hazardous materials (SAF/AQ, 1994). This type of command and control approach to environmental regulations is often inefficient. It is reactive rather than proactive, which does not encourage long term innovation (Costanza, 1996:91).

Arbitrarily concentrating on specific chemicals and attacking issues individually without a consolidated approach or an understanding of long range impacts may not be effective. Pollution prevention goals are often driven from the top-down with no consideration of how to optimize them across the acquisition process as a whole. Instead of envisioning the pollution prevention process as a whole and concentrating

on long term goals, individual program offices often develop fragmented or inconsistent pollution prevention approaches to accommodate the top-down guidance received. This is compounded by the fact that the various influences and mechanisms that should optimally drive the pollution prevention process are not fully known or documented across the acquisition field.

In order to be effective, environmental considerations should be incorporated into decision making (Costanza, 1996:91). In addition to top-down pollution prevention guidance, some acquisition program managers are incorporating pollution prevention into their decision making process. One common approach is to evaluate pollution prevention effects during the design decision process from a LCC perspective. LCC is all the costs of a weapon system over its entire life cycle, from acquisition, through operation and maintenance, and including disposal (Curran, 1996:6.2). LCC is a good tool to measure the effects of pollution prevention efforts in the standard weapon system acquisition metrics of cost, schedule, and performance, because in the typical acquisition program, impacts to these metrics are eventually converted into LCC. Also, converting dissimilar attributes of a design to cost allows for comparison of the attributes in common terms (Prasad, 1997:39). Thus, expressing pollution prevention efforts in terms of LCC allows these efforts to be compared to the other "ilities" of the acquisition process, such as producability, survivability, and maintainability.

Minimizing a system's LCC while meeting performance requirements is the ultimate goal of the design decision process. However, it should be noted that although optimizing life cycle cost may help ensure pollution prevention is incorporated along with other program "ilities" when making the most effective design decision for a program's life cycle, other influences, such as policy, laws, regulations, finances, and

the program's development phase also affect how pollution prevention is incorporated into the design process (Heinz and Wireman, 1993:36). Pollution prevention affects more than the program design. Pollution prevention efforts integrated into the design decision process typically affect the budget, production, maintenance, operation, and disposal of a weapon system. Also, when pollution prevention efforts are implemented as part of the decision process, they are influenced by and must be closely integrated with systems engineering, logistics, contracting, program management, and other functional areas within the program.

The integration of these pollution prevention influences and mechanisms into the weapon system acquisition process is complex, and many of these influences may feed back into other parts of the overall process. People try to develop causal relationships in their minds between what influences the pollution prevention process and the mechanisms by which the pollution prevention process work; these causal relationships are referred to as cognitive or mental maps. Because people's mental maps contain few if any feedback loops (Sterman, 1996:105), and because of the complexity and dynamic nature of the pollution prevention process in weapon system acquisition, people's mental maps of the pollution prevention process may be inaccurate. Because the pollution prevention process is complex, and to allow for the presence of feedback loops, a structured process is needed to help document the mental maps of the influences and mechanisms of the pollution prevention process. Also, since other influences effect the implementation of pollution prevention projects besides LCC, the pollution prevention acquisition design process needs to be examined at a higher systems level view to include these additional influences.

Specific Research Issue

There is a need to optimize pollution prevention efforts in weapon system acquisition to reduce costs over the system's life cycle. A lack of understanding of the dynamic interactions of pollution prevention drivers, influences, and mechanisms inhibits understanding pollution prevention on a systems level and prevents the optimal implementation of pollution prevention to reduce system LCC. The pollution prevention influences having the greatest affect on reducing program LCC need to be identified so that dwindling management resources can be concentrated in these areas. Due to the complexity of the influences and decision rules of the pollution prevention acquisition process, an aid is needed to document the decision rules, assumptions, and the mental model of this process. Modeling of the pollution prevention acquisition process would facilitate simulation of the system.

Research Questions

The purpose of this thesis is to develop a system structure for the pollution prevention acquisition process and use modeling simulations to develop management strategies that optimize life cycle cost. To accomplish this task, the following research questions must be answered:

1. What are the primary pollution prevention influences, mechanisms?
2. How do the pollution prevention influences and mechanisms interact and affect the acquisition process?
3. How can key pollution prevention influences and mechanisms be effectively managed to reduce life cycle costs?

Scope

This project examines and documents the interaction of the pollution prevention influences with the acquisition process over the life cycle of a typical weapon system. Examination of this process uses a modeling technique that allows for the inclusion of feedback loops, which should provide a benefit over the standard decision analysis methods, which do not account for feedback. Modeling also benefits this project because of the need to encode a large set of interrelationships and because simulation facilitates the investigation of how external changes affect the overall system. Simulations of the system also help analyze trends and alternative scenarios, and helps determine which pollution prevention influences have the greatest effects on a program's LCC. The model addresses the entire life cycle of a weapon system from concept exploration through disposal of the system.

Limitations

It should be recognized that different weapon system acquisition programs are of different complexity and have different performance requirements; therefore, actual system parameters and variables may differ. Because literature that addresses the actual implementation of pollution prevention in the weapon system acquisition process is limited, most of the information presented is based on personal experience and the results of a few surveys, audits, and reports. Also, because cost-based accounting, which tracks specific environmental costs, has not been widely implemented, there currently is limited separable data available for hazardous material costs in weapon systems. However, as explained in Chapter 2, it is the general purpose of the system

dynamics model to demonstrate general trends and not provide specific cost numbers for certain types of weapon systems.

Thesis Overview

Chapter 2 briefly addresses the acquisition process, the goals of pollution prevention, and requirements that drive the Air Force to implement pollution prevention efforts. Current Air Force pollution prevention practices are also summarized. Chapter 3 addresses the methodology of constructing and validating the selected model. Chapter 4 presents the results of the validation process, the sensitivity testing, and the testing of various policy and management scenarios. Chapter 5 presents the discussion and conclusion of the model results.

2. Literature Review

Overview

This literature review addresses the very basics of the Air Force weapon system acquisition process and the weapon system life cycle phases. The fundamentals of pollution prevention are discussed, as well as the regulatory drivers that implement pollution prevention in the Air Force. Finally, the modeling process is discussed, including the practice of modeling management systems.

Pollution Prevention

Under the current Air Force conditions of reduced budgets and personnel levels, program managers are being asked to do more with less money and human resources. With LCC of sophisticated aircraft nearing one billion dollars per aircraft (DAU, 1997:315), optimum execution of program acquisition is essential in order for program managers to reduce overall costs to their programs and to stretch limited budget dollars. One possible avenue of reducing program costs is to reduce the significant cost associated with the use of hazardous materials. It is estimated that costs associated with hazardous materials are $750 million for the F-16 fleet and $500 million for the B-1 fleet (AFMC, 1992:2-12). The implementation of a pollution prevention program could reduce the costs associated with the use of hazardous materials in weapon systems.

In addition to reducing hazardous substances, pollutants, and contaminants, pollution prevention programs also conserve raw materials and energy, reduce wastes, and lower hazardous material management and disposal costs. Criminal and civil

liability and public health risks are also reduced when the amount of hazardous materials is lowered (EPA, 1994:2). Because the Federal Facility Compliance Act amendment to RCRA waives sovereign immunity for the DoD, government program and facility managers are now held equally accountable for environmental compliance issues with their counterparts in industry. This means, in addition to the potential cost savings, program managers should also be motivated to initiate pollution prevention to reduce their liability.

The Air Force implements the Pollution Prevention Act through Executive Orders, DoD Directives, Air Force Directives and policy letters, but the focus has changed slightly from this broader view of pollution prevention. Due to the high cost of cleaning hazardous materials up after-the-fact, the strategy has changed to reducing pollution at the source (AFMC, 1996b:1-1). Presidential Executive Order 12856, "Federal Compliance with Right-to-Know Laws and Pollution Prevention Requirements" focuses on pollution prevention through source reduction in facility management and in acquisition (Talts and Werle, 1993:1-4). In the Secretary of Air Force Action Memorandum on the U.S. Air Force Pollution Program, 7 Jan 93, two of the six Air Force pollution prevention objectives referenced call for the reduction in the use of hazardous materials in all phases of new weapon systems and existing weapon systems (SAF, 1993). In addition to concentrating Air Force pollution prevention efforts on source reduction, specific lists of chemicals are often highlighted. For example, Air Force Instruction 32-7080 requires a reduction in the use of chemicals on the Environmental Protection Agency's 17 Toxic Chemical List (AFI 32-7080, 1994:6).

The National Environmental Policy Act (NEPA) is implemented through the Air Force's Environmental Impact Analysis Process, of which pollution prevention is a

major element. Federal agencies are instructed to list a program's pollution prevention efforts, include pollution prevention considerations in the alternatives, describe how pollution prevention efforts are implemented, and document how pollution prevention reduces adverse impacts. NEPA and DoDI 5000.2 require the status of a program's environmental program be summarized in an environmental analysis at each milestone decision point (AFMC, 1996b:3-40). Pollution prevention and NEPA both consider environmental impacts, energy requirements, and mitigation; however NEPA addresses top level or macro-level processes. (Salomon, 1994:63)

DoD Directive 4210.15, Hazardous Material Pollution Prevention focuses pollution prevention efforts to source reduction by stating:

> It is DoD policy that a hazardous material shall be selected, used, and managed over its life cycle so that the Department of Defense incurs the lowest cost required to protect human health and the environment. The preferred method of doing this is to avoid or reduce the use of hazardous materials. (DoD, 1989)

DoD 4210.15 also urges hazardous materials costs be considered at the earliest life cycle phases.

Acquisition pollution prevention helps programs avoid slips in their schedules, reduces the program's life cycle cost, and improves environmental quality (AFMC, 1993:2). Schedule slips are avoided by reducing NEPA requirements, the need to build elaborate facilities to handle hazardous materials, or the reduced efficiency of having to work in Personal Protection Equipment (PPE). Life cycle costs are lowered by reducing raw materials and energy, reducing wastes, and lower hazardous material management and disposal costs. Environmental quality is improved because reducing the amount of hazardous materials lowers the risk of adverse environmental impacts and protects public health. According to the EPA, pollution prevention has saved millions of dollars

in treatment, compliance and acquisition costs. Pollution prevention eliminates fines related to waste mishandling, which could possibly be as much as $25,000/day/fine, and pollution prevention also reduces disposal costs for hazardous materials and waste, which have increased ten fold since 1988 (Hudson, 1995:1 & 10).

Acquisition Process

Currently, the DoD is moving away from specifying how a contractor should build a weapon system and is concentrating on whether the system meets performance requirements. This relaxing of specifications is observed as the DoD changes from the citing of military specifications to the use of private-sector standards whenever possible (Talts and Werle, 1993:4-3). Demanding performance requirements, which are now the main driver for material selection, often require the use of hazardous materials to meet rapid drying times for paint, high cleanliness of parts, or lighter weight composite materials. Performance requirements actually begin prior to an acquisition program starting, when a Mission Area Analysis (MAA) is performed to see if a future threat or projected capability can be met. If the MAA identifies a need, a Mission Need Statement is developed to document the deficiency. Next, an Operational Requirements Document is developed to specify the top level performance requirements necessary to meet the operational need. These performance requirements describe the characteristics and capabilities the system must have to meet the identified deficiency (DAU, 1997:64-67).

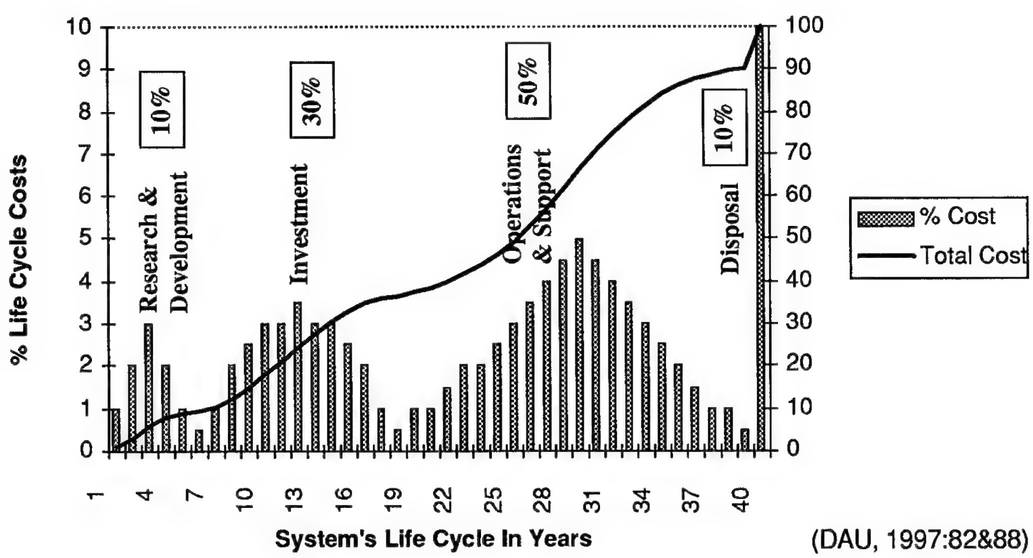
Program Phases. The program and design decisions made in the early phases of the program life cycle can lock in the use of hazardous materials and their associated costs early on in the system's life cycle. The first program phase, Concept Exploration (CE) begins after the mission need is verified and the performance requirements are

developed. The CE Phase of the acquisition program typically lasts one to two years. A few of the objectives of the CE phase are to identify the high risk areas, develop management approaches for these risks, and develop the best system concept for meeting the mission need (DAU 1997:416). It is estimated that 70% of the life cycle costs are set during the CE phase due to the decisions that are made (DAU, 1997:323). Next, the Program Definition & Risk Reduction (PDRR) Phase lasts for two to four years. The main objective of the PDRR Phase is to define major design characteristics, ensure technologies can be incorporated into the design, and identify possible environmental impacts (DAU, 1997:423-424). Pollution prevention considerations should be an integral part of the trade-off studies conducted during this phase of the weapon system's life cycle. It is estimated that during PDRR, 85% of the life cycle costs of the design are set.

The next program phase is the Engineering and Manufacturing Development (EMD) phase, which lasts for approximately four to seven years. In this phase, the design is finalized and trade studies occur to ensure the design is producible, supportable, and cost effective (DAU, 1997:429). At this point in the program, it is estimated life cycle costs are now 95% fixed (DAU, 1997:323). The last program phase is Production, Fielding/Deployment and Operational Support. The goals of this phase are to achieve efficient production, and ensure an operational capability is reached that meets the mission need (DAU, 1997:437). Production can last for several years, depending of the maximum production rate, total quantity of the units produced, and funding to buy units. The program life of an aircraft unit is typically planned for 25 years, but can be much longer, as in the case of the B-52 bomber. The program life cycle finally ends at

disposal, where the units are demilitarized and placed in storage at Davis-Monthan Air Force Base, Arizona.

Life Cycle Costs. Life cycle costs for a weapon system program can be exorbitant. It is believed that life cycle cost for one sophisticated aircraft is nearing $1 billion (DAU, 1997:315). The life cycle cost of a program covers all its costs over its entire life and includes research and development, investment, operation and support (such as software, hardware, facilities, environmental), and disposal costs. Research and development costs cover CE, PDRR, and EMD Phases, while investment costs cover production and deployment. It is estimated that life cycle costs break down as follows: Research and Development costs 10%; Investment Costs 30%; Operations and Support 50%; and Disposal 10% (DAU, 1997:81-88). These life cycle costs are represented in Figure 1.



(DAU, 1997:82&88)

Figure 1: Notional Life Cycle Cost Spread

Some estimates that provide insight into the hazardous materials contributions to the overall life cycle costs are that 80% of handling, treating, and disposal costs in DoD

facilities are directly related to weapon system operations, maintenance, and disposal. Also it is believed that for every $1 used to purchase hazardous materials, it costs $80 dollars over life cycle to manage, control, and dispose of these materials. Typically, Environmental Safety and Health (ESH) costs are considered high if they are 10% or more of life cycle cost (EER System, 1996:13).

Research by The Analytical Science Corporation (TASC) has shown that the following seven cost drivers account for 94% of total hazardous materials costs: personal protection, legal/environmental, medical, procurement, monitoring, disposal, and handling. Other minor cost areas identified by TASC include support equipment, facilities, training, & transport (TASC, 1994:7). To further define these seven major cost areas, Air Force Materiel Command has estimated 81% of hazardous materials costs come from only four main areas: procurement, legal/environmental, personal protection, and disposal (AFMC, 1993:11). According to the Air Force Materiel Command (AFMC) Pollution Prevention Guide, these costs include the following, which are not readily accounted for during the acquisition phase of the program:

- Procurement
  - Cost of Material
  - Cost to transport material from manufacturer to point of use
- Personal Protection
  - Cost of equipment to protect personnel from hazardous materials/waste
  - Cost to distribute and track personal protection equipment
  - Cost of lost productivity resulting from use of protective equipment
- Legal/Environmental
  - Cost of settling toxic tort claims
  - Cost of regulatory authority correspondence
  - Cost of real property damage
  - Cost of contaminated water treatment
  - Cost of natural resource damage
- Disposal
  - Cost of industrial wastewater treatment plant
  - Cost of waste collection, handling, permits and licenses
  - Cost of analysis and classification of hazardous waste
  - Cost of contractor disposal of hazardous waste (AFMC, 1993:A-9)

Acquisition Costs. As mentioned above, most of the life cycle costs of a program are set in the earlier phases such as CE or PDRR; however, the majority of the life cycle costs actually occur after CE and PDRR, during production, operation and support, and disposal. Although under the Integrated Weapon System Management process, the program manager is responsible for the costs of the weapon system over its entire life cycle, program managers are only required to formally brief the system's LCC during the milestone review at the beginning of each new program phase (DoD 5004). Program managers, in the earlier phases of a program, typically concentrate on the acquisition costs, which cover developing and buying all the weapon system units and should not be confused with life cycle costs, which are the total costs to operate the system over its life cycle. Weapon system acquisition or procurement costs are usually tracked using the Earned Value Management System (EVMS), formally the Cost/Schedule Control System Criteria.

The EVMS is required to track acquisition costs on DoD development contracts over $70 million and production contracts over $300 million. The EVMS summarizes the cost, schedule, and technical accomplishments of a program. The EVMS compares cost of work accomplished with the cost of work planned and estimates the at-completion cost of a program (DAU, 1997:207-210). EVMS only accounts for cost at the lowest level of functional responsibility, such as systems engineering, (DAU, 1997, 210). It is normally expensive and cumbersome to track program costs below the second or third level of functional responsibility, so pollution prevention costs, which are incurred at lower functional levels, are often lost. The EVMS is designed so all contractors can use their own cost accounting systems (DAU, 1997:207), and since most contractors accounting systems do not handle ESH costs, costs tracked by the

contractors cannot contribute to government estimates of ESH costs (EER Systems, 1996:30). Because the costs tracked by the EVMS do not reflect pollution prevention costs or total life cycle cost impacts, and because total life cycle costs are only briefed at major milestone reviews, the incentive to perform pollution prevention efforts to save money cannot always be seen in the earlier program phases.

Accomplishing Pollution Prevention

It is fairly clear that the intent is to implement pollution prevention through the systems engineering process. The Secretary of Air Force Acquisition Office Policy Letter, 93M-001, states that acquisition pollution prevention should be implemented by integrating the DoDI 5000.2 environmental requirements into the systems engineering decision process to ensure cost effective solutions are implemented (SAF/AQ, 1993). While DOD 5000.2-R Section 4.3.7 requires the integration of ESH into systems engineering, AFMC also advises the single manager to use the integrated product development process and systems engineering process to implement pollution prevention into the acquisition process (AFMC, 1996b:iii).

Pollution prevention incentives are considered during the earlier phases of the acquisition during the Integrated Product and Process Development process, which considers all tasks across the life cycle in the design and development process (DAU, 1996:229) Integrated Product and Process Development is implemented through the systems engineering process by a multidiscipline integrated product team. The systems engineering process translates the system's general operational requirements into system specific requirements. Part of this Systems Engineering process is systems analysis and control, which includes technical reviews and trade studies.

Cost, schedule, and performance are normally the most important factors in these tradeoff decisions (DAU, 1996:224 & 253). During the trade studies, converting dissimilar attributes of a design to cost allows for comparison of the attributes on common terms. (Prasad, 1997:37). Typically the government provides key tasks to the contractor, and the contractor performs a majority of the systems engineering work through the formation of interdisciplinary teams (DAU, 1996:236).

In addition to the author's experience in the pollution prevention programs in weapon system acquisition, insight into the current practices of System Program Office (SPO) personnel can be gained by examining the thesis work of Donna Heinz and Dudley C. Wireman. They conducted a qualitative exploratory study of pollution prevention in acquisition programs by surveying Aeronautical System Center (ASC) contracting and environmental management SPO personnel, personnel from the ASC Environmental Directorate (ASC/EMV), and personnel from the Secretary of the Air Force for Acquisition (SAF/AQ). Their 1993 survey of ASC and SAF personnel showed SPOs had environmental programs, however pollution prevention programs were just starting or did not exist and most pollution prevention programs were driven by compliance needs (Heinz and Wireman, 1993:36&39) instead of a life cycle cost savings strategy.

Pollution Prevention Influences

When examining the pollution prevention process in weapon system acquisition, a few entities surface as the main drivers. Heinz and Wireman observed in their survey of ASC and SAF/AQ that most pollution prevention programs are driven by funding, environmental law, and the program's acquisition phase. Newer programs were

proactive because they are able to request funding and implement changes in the design, while mature programs were reactive because they could make little changes and had difficulty obtaining funding (Heinz and Wireman, 1993:36&39)

Weapon system contractors' efforts in acquisition pollution prevention are driven by compliance with federal, state, and local laws that affect the manufacturing of the system(AFMC, 1996c:2-15), but contractors are not actively pursuing pollution prevention over the life cycle. The increased cost of pollution prevention and the past citing of military specifications that required the use of hazardous materials have inhibited contractors' pollution prevention efforts although, most SPO contracting and environmental management personnel believe state environmental laws could drive contractor's efforts as the laws become more stringent (Heinz and Wireman, 1993:38,45,51, & 67).

Not only is the development of non-hazardous material substitutes necessary, but the sharing of this information is key for successful pollution prevention. Surveys again indicate that single program managers design their own pollution prevention programs with little sharing of information and lessons learned, and there is concern among the program managers over the lack of information shared regarding material substitutions (Shah, 1997:22; Heinz and Wireman, 1993:38 & 54). Currently, information clearinghouses are poorly organized, increasing the difficulty in finding substitution information. Searching the pollution prevention information clearinghouse is time consuming and does not ensure an exhaustive search (Foecke and Style, 1992:226). Knowledge of hazardous material substitutes is essential if pollution prevention efforts are to be incorporated by the systems engineering process.

As mentioned earlier, the systems engineering process is the preferred method of implementing pollution prevention. Most SPO personnel prefer this over the value engineering change proposal, which is time consuming and cumbersome (Heinz and Wireman, 1993:56). The value engineering change proposal identifies possible changes that can be made to the existing system to save money over the system's life cycle. However, this process is time consuming and cumbersome because systems drawings and configurations must be changed and the impacts of any changes and any possible perturbations through out the entire system must be thoroughly examined. Within the systems engineering process and integrated product and process development, the Environmental Working Group is the primary vehicle for implementing pollution prevention (AFMC, 1996b:1-12). The meetings and informal contacts that occur during the IPD process are the key methods for exchanging information and implementing pollution prevention. Policy and guidance is least effective (Heinz and Wireman, 1993:39 & 43), perhaps due to the specific nature of the guidance concentrating on lists, as discussed previously, instead of actual efforts that were of primary importance to the specific weapon system.

Contracting is another important entity of pollution prevention. It is important to incorporate pollution prevention requirements in the first three acquisition phases, through source selection criteria and award fee incentives, because the further along a program is in the acquisition phase/cycle, the less contract managers can modify contracts to incorporate pollution prevention programs (Heinz and Wireman, 1993:54 & 37). Part of the contracting process is source selection, where the contractor is chosen to build the weapon system or unit. Here it is important to embed environmental criteria into the performance appraisal process to make it effective; otherwise, near term

financial aspects win out when there is a conflict with the environment (Gray and others, 1993:161,164).

Yet another important entity that helps consolidate and implement pollution prevention efforts is the Environmental Safety and Occupational Health (ESOH) Technical Planning Integrated Product Team (TPIPT), which is currently responsible for prioritizing the hazardous materials reduction efforts at Air Force Materiel Command. As part of the Technology Master Process, environmental and pollution prevention technology needs are identified to the ESOH TPIPT by Major Commands, Air Logistics Centers, product centers, and SPOs' system engineering functions. Projects are then prioritized by the ESOH TPIPT (AFMC, 1996c:2-5). Only the projects awarded science and technology dollars are implemented. Projects are then executed by the Air Force Research Laboratory or the appropriate AFMC center (AFMC, 1996c:2-6).

Limited funding prevents the Air Force Research Laboratory from undertaking all but the highest priority pollution prevention substitution programs. DoD wide, funding for basic research is comparatively small; it only accounts for 5% of total national funding for basic research. Of this small amount, less then 25% is spent at Federal laboratories. Regarding applied research, the funding in this area must be spread across ten key areas. This also limits funding the Air Force Research Laboratory receives. Additionally, only a small portion of research funding is accomplished through weapon systems programs because research projects are generally not feasible or mature enough to include in the systems acquisition process due to the increase in program risk (DAU, 1997:276-277).

Policy is not an appropriate tool for efficiently implementing pollution prevention actions. Policy typically acts as a guide for an organization's future actions, sets

parameters and boundaries, and prioritizes issues. Generally it must communicate to a wide varied audience and there is no standard policy for all applications (Brophy, 1996:93). In addition to omitting specific guidance for implementation, a Massachusetts Institute of Technology study has found Air Force pollution prevention directives and policies are often developed without the simultaneous development of appropriate tools. The study cites an example where Air Force policy requires the life cycle cost impacts of all materials to be studied; however, an approved life cycle cost estimator does not exist for this purpose (Shah, 1997:20-24). This causes program managers to tend to ignore these directives and policies. Another weakness of pollution prevention policy is that top level management commitment is necessary for policy success (Brophy, 1996:93). The policies' effectiveness also rely on the program managers commitment which can change considerably from program manager to program manager. Brophy goes on to explain that environmental policies normally focus on issues that financially benefit the organization and legislative compliance is given precedence and is the most important factor driving environmental action (Brophy, 1996:102). This again means that pollution prevention efforts are concentrating on the financial LCC aspects and rely more heavily on laws and regulations.

Need for Systems Approach

Much literature addresses the appropriate environmental documentation, incorporating pollution prevention into the systems engineering process and tracking metrics of eliminating specific materials. Other literature addresses the importance of life cycle assessments but ignores the feedback of these future life cycle impacts into

the on going pollution prevention process. However, there appears to be a lack of literature on the overall system interactions of the pollution prevention process. For example, the MITRE guide, ***Pollution Prevention and the Acquisition of Aircraft Weapon Systems*** prepared in 1992 for the Aeronautical Systems Center, is an informative document that covers the impacts of hazardous materials, current aerospace initiatives in pollution prevention, and how the hazardous materials identification and evaluation process should work (Lynn and Sylvestre, 1992:multiple). But the document does not address how these aspects are interrelated and influence one another.

Another guidance document that does not address a systems approach to pollution prevention is the ***Weapon System Pollution Prevention Applications Course Student Guide***. It addresses pollution prevention applications and tools, but does not present a systems perspective on how these applications interact with and influence each other. A systems approach is needed that examines all the pollution prevention variables at once, considers the feedback between the variables, and allows for the changes in the variable's effectiveness as an acquisition program progresses through its life cycle.

System Dynamics Modeling

One type of model that examines behavior on a system level, while allowing for complex interactions and feedback between variables, is a system dynamics model. System dynamics modeling can be used to diagram the concepts and relationships within a system (Richmond and others, 1994:4), and the system dynamics' methodical process of identifying the system's structure and behaviors is very helpful in the

conceptualization of the process under study (Randers, 1996:285). Coding the pollution prevention process into system dynamics software captures a mental model of how things work, encourages cooperative learning, exposes blind spots in the process, and documents assumptions (Richmond and others, 1994:13). An indirect benefit of computer modeling is the improvement of the mental model (Vennix, 1996:343). To help better document cognitive or mental maps of the causal relationships in the acquisition pollution prevention process, system dynamics modeling is used in this project.

System dynamics modeling differs from other types of modeling. In a steady state model, the inputs and states do not vary with time. In a deterministic model all variables are computed exactly and most values are known. In a probabilistic model, the parameters are within a known distribution. However, in a system dynamics model, the variables and states change over time (Gordon, 1985:16-17). Another key feature of system dynamics is circular causality. Richmond explains circular causality is when "each of the causes is linked in a circular process to both the effect and to each of the other causes." Circular causality is represented in a system dynamics model by feedback loops. The effects of the feedback loops increase and decrease over time, so different loops dominate over time (Richmond, 1996:30). The presence of feedback loops allows the variables and states within the system to change over time. Positive feedback loops reinforce the initial action or behavior and are considered destabilizing because unchecked, they drive accelerated growth or collapse of a system. Negative feedback loops oppose the initial action or behavior and are considered stabilizing or goal seeking (Richmond, 1996:49).

System dynamics goes beyond just listing what factors are correlated with an behavior. System dynamics seeks to develop operational explanation of how a system's behavior is generated, and how the dynamics of the system change over time (Richmond, 1996:30). A system dynamics model takes more of a top level or generic view of a system, where the goal is to determine the simplest set of influences that explain the system's behavior. In system dynamics, it is considered that the dynamics are generated by the system itself, due to the closed loop relationships and interdependence of the feedback loops (Richmond, 1996:26). Since system structure is viewed as the cause of behavior over time, all the dynamics of the system must be included inside the modeled system boundary. The system is viewed as a closed loop so there is no distinction between cause and effect; the relationships continually feed back on one another. Operational thinking is used to determine physically how the system really works (Richmond and others, 1994:23-30).

Advantages. System dynamics is a good tool to use for organizing the complexity of a management system (Mass, 1996:398). When making management or policy decisions, people are unable to analyze several variables at a time, which often limits the complexity of their decision making (Gordon, 1985:4). People's mental maps (causal connections of the influences developed in a person's mind) seldom incorporate feedback loops, multiple interactions, time delays, and non-linear interactions. Adding dynamic changes over time introduces even greater complexity, which causes people to perform below potential (Sterman, 1996:103-106). The system dynamics process accounts for feedback loops, multiple interactions, time delays, non-linearity, and changes in the system over time. The structure of the system dynamics process helps to identify the underlying mechanisms that drive the basic system

behavior. Policy makers knowledge and system information can be coded into the system dynamics model (Morecroft, 1996:191), which enables people to understand both the short-term and long-term consequences of their management alternatives.

Examples. System dynamics modeling has been used to model systems similar to pollution prevention in weapon system acquisition. Kenneth Cooper's computer simulation model addressing a DoD acquisition related problem used a system dynamics computer simulation to determine what caused cost and schedule overruns on two of the Navy's billion dollar ship building programs. The model was used to settle a $500 million claim against the U.S. Navy. The model now helps with strategic management of shipyard operations, and it can be used to evaluate the impacts of changes in policies, contract management, work schedules, resource management and cost forecasting (Cooper, 1996:425). For the design, procurement, planning, and production stages of the shipbuilding programs, the model quantified costs of Navy delays and disruptions due to design changes. The model was designed to replicate the management and policy decisions and operations of the shipbuilding company (Cooper, 1996:429). The Navy shipbuilding acquisition process is affected by management and policy decisions much in the same way the Air Force pollution prevention acquisition process is affected by management and policy decisions.

Although some influences in the pollution prevention acquisition process are not readily measurable, a system dynamics model can still be used. In a work published in "System dynamics Review" magazine, Jack Homer uses soft variables, quantities that are not readily measurable, such as stress, burn out, and energy level, to construct a dynamic model of worker burn out (Homer, 1996:453). In his model, Homer examines the workaholic's ability to cope with a stressful job. Although little literature was

available on repeated cycles of burnout, Homer used logic and considered judgment to develop his parameter values for the model. For example, an arbitrary unit of accomplishment per hour was established for the work. When the worker's energy level was full, the worker produced one unit of accomplishment. This decreased with energy until at zero energy, the worker produced nothing. The model was able to accurately reproduce the cycle of work burnout along with appropriate rise and falls in hours worked per week, accomplishments per week, energy level, and perceived worker adequacy. Simulation runs of the model replicated real world burnout scenarios, and the model tests were able to confirm five factors can affect the stability of the burnout cycle (Homer, 1996:454-470).

The first example demonstrates system dynamics modeling has successfully been used to model Navy weapon system acquisition processes, which are basically similar to the weapon system acquisition processes in the Air Force. In the second example it is evident that even though variables and influences are not readily measured, they can still be represented as soft variables in a system dynamics model. This proves quite useful, since many influences in the acquisition pollution prevention process, such as the incentive to perform pollution prevention, are not easily measured.

Summary

This chapter reviewed how pollution prevention efforts are flowed down within the Air Force, and it also addressed the benefits of performing pollution prevention. The various acquisition phases, the cost associated with these phases, and the amount of design solidification in each phase was also discussed. The various pollution

prevention influences within the acquisition program were presented as well as why the project would benefit from a system dynamics modeling effort. In the next chapter, the standard methodology for implementing the system dynamics process is presented.

III Methodology

Approach

Because of the complexity of the weapon system acquisition pollution prevention process, to incorporate the feedback of the various influences within the process, and to allow for the dynamic changes in pollution prevention effectiveness over the life cycle of the weapon system, a system dynamics approach is used for this project. The developers of system dynamics software suggest the following steps for system dynamic modeling: (1) focusing the effort, which includes the development of a reference mode and a system diagram; (2) mapping, which involves identifying the key actors of the system; (3) modeling, which consists of developing flows, causal loops, and setting parameter values and equations; and (4) simulation, which consists of running the model, fixing mistakes, and replicating the reference mode (Richmond and others, 1994:153). It should be noted this is an iterative process and the steps do not necessarily happen in a sequential manner. Further confidence is gained in the working model through use and validation testing.

This chapter addresses the methodology of building the system dynamics model. The first step is to determine what behavior over time to study in the acquisition pollution prevention process. Then an influence diagram (system/causal diagram) is developed that reflects the main causes of this behavior. This influence diagram, along with the aggregation of influences and the relationships between the influences are briefed to personnel and collocates in the ASC Environmental Directorate. Comments are incorporated and the influence diagram updated. Next the influence diagram is coded into STELLA II ®. The model is run and mechanical mistakes fixed. The model

is also run to match the hypothetical reference mode and further modifications are made to the model so it more accurately represents the real world system and more realistically matches the reference mode. Finally, after performing validation tests to further gain confidence in the model, sensitivity analyses and policy scenarios are run. This is an iterative process; further confidence is gained in the working model the more it is used.

Reference Mode.

The reference mode is the observed behavior of the entity under study over the time of interest. The reference mode is established to keep the study focused on the variables involved that explain the behavior of the system over time. It is important to identify the reference mode behavior first, and then examine what is causing the behavior. Care is taken not to start by describing the entire system, but instead, to only include the mechanisms that are a major cause of the reference mode (Randers, 1996:287-288).

Once a reference mode is chosen that adequately represents intuitive responses to the perceived pollution prevention influences in the weapon system acquisition process, closed loop and operational thinking are then used to identify what behaviors drive the reference mode. Closed loop thinking helps ensure the causes of the system's behavior are accounted for in the feedback loops identified. Operational thinking looks beyond how the system theoretically works, and identifies what actually physically causes the system to work in reality (Richmond, 1996:36&39).

Influence Diagram.

Once the reference mode is identified along with the major mechanisms that cause the reference mode, feedback between the various mechanisms are identified. An influence diagram or causal diagram is developed to show the top level mechanisms and key feedback loops of which the main system is composed. The Influence diagram helps portray the influences and how they interact to generate the observed system behavior (Richmond and others, 1994:154). The feedback loop diagrams also help lay out the structure of the complex pollution prevention system and communicate model insights (Richmond, 1996:49). The feedback loops are identified as either positive or negative. Positive feedback loops are considered unstable because they continually reinforce the same behavior, which leads to uncontrolled exponential growth or decay. Negative feedback loops are considered stabilizing because they counter or work to control behavior, which drives the system to a predetermined goal. Once the top level influence diagram is complete, the feedback loops are identified as positive (unstable) or negative (stabilizing).

Model Construction.

Once the influence diagram is completed, the key mechanisms of the system are identified and coded into the system dynamics software. The software represents the system through a series of stocks, flows, converters, and causal loops. Stocks accumulate items, such as the total amount of hazardous materials selected. Flows add and deplete items for stocks, and converters control the flows and convert items, such as converting the amount of hazardous materials into an amount of hazardous waste. The causal loops are the feedback loops identified within the system. Once the

stocks, flows, converters, and causal loops are modeled, parameters values entered and equations that represent the interrelationships are coded into the model. The policy makers knowledge and system information is also coded into the model. The feedback loops in the model are based on the behavioral decision theory identified by the policy makers. (Morecroft, 1996:191). The casual relationships are based on decision rules used by the actors of the system, not correlations to historical data (Saeed, 1996:307). Once the model is constructed and initial tests are run, if the model behavior does not match the reference mode, the model structure is reexamined and modified (Saeed, 1996:308) to more accurately reflect the mechanisms of the real world system.

The system dynamics software used with this project is developed by High Performance Systems, Incorporated and is called STELLA II ®. The STELLA II ® software interfaces with the user in a system dynamic context and facilitates the quantitative structuring of the influence diagram. The Euler method, one of the numerical integration methods available in STELLA II ®, is used to perform the integration for this model. To go from a detailed mental model to a less detailed and more abstract STELLA II ® model, the influences are aggregated and then a top-down iterative approach is used to flesh out the details to an appropriate level (Richmond and others, 1994:132).

As the model's life cycle time line progresses, the following are addressed: (1) the increased difficulty in making engineering design changes; (2) the increased cost in implementing pollution prevention changes; (3) the increased cost savings of reducing hazardous materials required in the operational phase; and (4) disposal concerns. The LCC is calculated to include acquisition budget and out year operational expenses.

Parameters & Qualitative Relationships. Based on literature, input from ASC environmental personnel, and personal experience, parameters and qualitative relationships of the system are also encoded into the model along with knowledge of the system and decision rules. Many of these variables do not have precise measurable values, so they are encoded into the model as soft variables. It is necessary to include these soft variables in policy or social system dynamics models because omitting them would fail to capture the key workings of the system (Richmond and others, 1994:157). When working with soft variables, it is important to distinguish between measurable and quantifiable. Measurable means assessing the magnitude numerically. Quantifiable means assigning a numerical index. Anything can be quantified by constructing an internally consistent index (Richmond and others 1994:158). Soft variables are coded into the STELLA II ® software by using a consistent index for all soft variables of 0-1. After the variable's range along the 0-1 index has been assigned, how much the difference in the soft variable impacts the influence's behavior is then determined (Richmond and others, 1994:158&160).

Model Adjustments. After the coding is complete, all the units for the stocks, flows, and converters are checked for consistency (Richmond and others, 1994:143). This involves ensuring days are not added to dollars or pounds and that all the units within the model's equations cancel each other to provide the expected output. The model is then run, and the causes of erroneous output are investigated to ensure the model structure accurately represents the mechanisms of the real life system. The model is also run to ensure its output over time is consistent with the behavior of the system predicted by the hypothetical reference mode. If the model's output does not match the reference mode, further modifications are made to the model structure so it more

accurately represents the real world mechanisms of the system and its output more realistically represents the reference mode.

Model Validation

As stated by Jay Forrester,

> "There is no single test which serves to 'validate' a system dynamic model. Rather, confidence in a system dynamics model accumulates gradually as the model passes more tests and as new points of correspondence between the model and empirical reality are identified." (Forrester and Senge, 1996: 413)

Because system dynamics modeling concentrates on overall system trends instead of predicting precise numbers, standard statistical tests are not used to validate the system dynamics model structure (Forrester and Senge, 1996:421). To gain further confidence in the model, the following standard system dynamics validation testing is accomplished on the model: Structure Verification, Parameter Verification, Extreme Conditions, Boundary Adequacy, and Behavior Anomaly (Forrester and Senge, 1996:416-431). Validation of the model to determine how the pollution prevention acquisition system really works is the core effort of this project.

The structure and influences represented in the model are compared to the real world mechanisms during Structural Verification. This is accomplished by directly comparing the model structure to the structure derived during the literature review, and then comparing the actual structure of the model with the structure of the real world system. Also, when explaining the detailed model structure to ASC Environmental personnel, they are asked to ensure the model structure is reasonable, that there are no contradictions between the model and the real world system, and that the assumptions in the model are valid.

Conceptual Parameter Verification is conducted by reviewing the parameters with ASC environmental personnel to ensure the parameters encoded in the model actually existed and matched elements in the real system. Numerical Parameter Verification is accomplished by having ASC environmental personnel also review and verify the numerical values and ranges of the parameters in the model.

The model's behavior during Extreme Condition testing is examined by setting the stocks and rates to realistic real world extreme conditions and observing the behavior of the model. It is important that the model does not crash and that the responding behavior seems realistic and is explainable.

Structure Boundary Adequacy is validated by explaining to ASC environmental personnel the aggregation of real world influences incorporated into the system dynamics model. ASC environmental personnel also reviewed the model to ensure all relevant structure is included and that no plausible hypothesis can be proposed that indicate the need for additional model entities or mechanisms. For example, the suggestion a program manager bribe mechanism be added would not be realistic, since this is not a plausible entity for this system. Behavior Boundary Adequacy is verified by ensuring the addition or removal of model structure does not affect the model's behavior. This means mechanisms that never activated or contribute little to the model during testing are removed without affecting the behavior of the model.

Behavior Anomalies, such as stocks or rates remaining constant or changing erratically during the model simulation, is observed during the initial coding and running of the model. This may indicate the model needs revision so it more accurately reflects the mechanisms of the real world system. The model is also tested to see if it shows implausible behavior when the assumptions are altered. Since important insight can be

gained by explaining counter intuitive model behavior (Morecroft, 1996:198), any surprise behavior (unnoticed behavior of the real system that surfaces during validation testing) is adequately explained.

Successful validation yields a sound and useful model, in which there is confidence that the model structure replicates the behavior of the real world system (Forrester and Senge, 1996:414). The model is now used to explore system policy questions, examine the sensitivity of certain system parameters, and test the system's structure.

Sensitivity Testing

Additional sensitivity testing is also performed. In addition to the above validation tests, Forrester lists Behavior Sensitivity, Policy Changed Behavior, and Policy Sensitivity as core validation tests. Behavior Sensitivity is performed by assessing the model's sensitivity to changes in key parameter values. Policy Changed Behavior is performed by assessing if the model correctly predicts how behavior changes with changes in policy (i.e. do changes in policy in the model yield plausible results). Policy Sensitivity is performed by identifying to what degree policy recommendations are affected by uncertainty in parameters values (Forrester and Senge, 1996:426-431). Finally, Influence Structural Sensitivity is performed on the model to ensure the top level influence diagram contains the true essence of influences in the pollution prevention acquisition process. The Structural Boundary Adequacy validation testing previously discussed are a very integral part of the Influence Structural Sensitivity, except the focus is to ensure the top level influence diagram includes all relevant influence structures and that no plausible hypothesis can be proposed that indicates the need for additional model entities or mechanisms.

Summary

In this chapter the standard process for developing a system dynamics model was reviewed. In this process, after the reference mode is established, an influence diagram is developed to account for the mechanisms that drive the reference mode behavior. Then the influence diagram is coded into the system dynamics software, and confidence is gained in the model as it progresses through system dynamics validation testing. Sensitivity testing and policy testing are then performed on the model. The next chapter applies these system dynamics modeling steps to the pollution prevention acquisition process. The results of the model validation testing and sensitivity testing are also presented.

IV Data Discussion and Analysis

Overview

In this chapter, the chosen reference mode and resulting influence diagram are presented. The process of using the influence diagram to guide the coding of the model and how the various acquisition pollution prevention mechanisms are represented in the model is then discussed (The actual STELLA II ® flow diagrams and equations are contained in the Appendix). The results of the validation testing and how the model output compares to the reference mode is reviewed as well as the adjustments made to the model to make it more accurately reflect the real world mechanisms of the pollution prevention system. Finally, the results of the sensitivity testing are discussed.

Reference Mode

Since cost is a common item for comparing dissimilar program influences, and because impacts to a program's cost, schedule, and performance are also converted to LCC impacts, LCC was picked for the reference mode. The premise is that pollution prevention efforts are implemented to reduce hazardous materials and hazardous waste costs, and thus reduce overall program costs. Therefore, as projected system costs increase above program goals, or as hazardous materials and hazardous waste costs become a larger percent of overall costs, pollution prevention efforts are implemented to try to lower overall LCC in the out years. As mentioned earlier, since specific environmental cost data is not maintained by the contractors and because ALCs do not track environmental costs at a program level, little historical data exists on

the effectiveness of pollution prevention projects over the life cycle. Therefore, a hypothetical reference mode was developed where the difference between the projected overall LCC and the program's LCC goal is examined as pollution prevention efforts are implemented. This concept is shown in Figure 2.

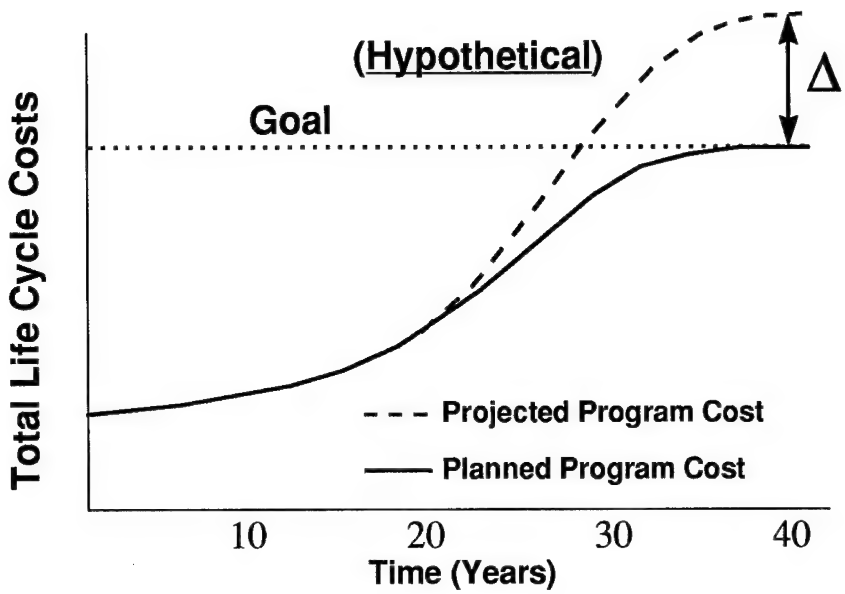


Figure 2: Projected LCC Compared to LCC Goal

Tracking the difference or delta (Δ) between the projected LCC and the LCC goal over time is another way to examine the reference mode. Since it is believed pollution prevention efforts would not reach their maximum until the delta between the projected and goal LCC is large, it is doubtful whether the cost is ever driven back to the original goal by pollution prevention efforts. This "Delta Reference Mode" is depicted in Figure 3.

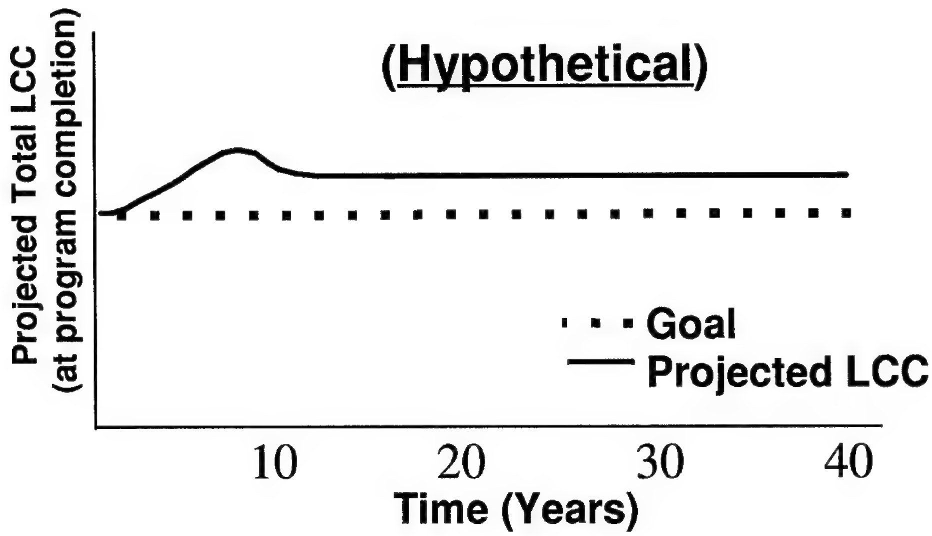


Figure 3: Projected Total LCC Reference Mode

Influence Diagram

The major mechanisms and feedback loops that cause the projected delta reference mode are represented in Figure 4. The Delta Above LCC Goal influence represents how high the costs to date plus the projected future costs are above the original LCC goal for the program. The Pollution Prevention Incentives influence represents the drive for the SPO to perform pollution prevention efforts. The Hazardous Material Substitutes influence represents the ability to find substitutes for hazardous materials or eliminate the use of hazardous materials. The Laws and Regulations influence represents the ability of Federal, State, and Local laws and regulations to incite pollution prevention efforts for both the SPOs and weapon system contractors. The Contractor Efforts influence represents the pollution prevention efforts the weapon system contractors perform just in the normal course of doing business. The Lab Efforts influence represents the pollution prevention efforts underway at the Air Force Research Laboratory.

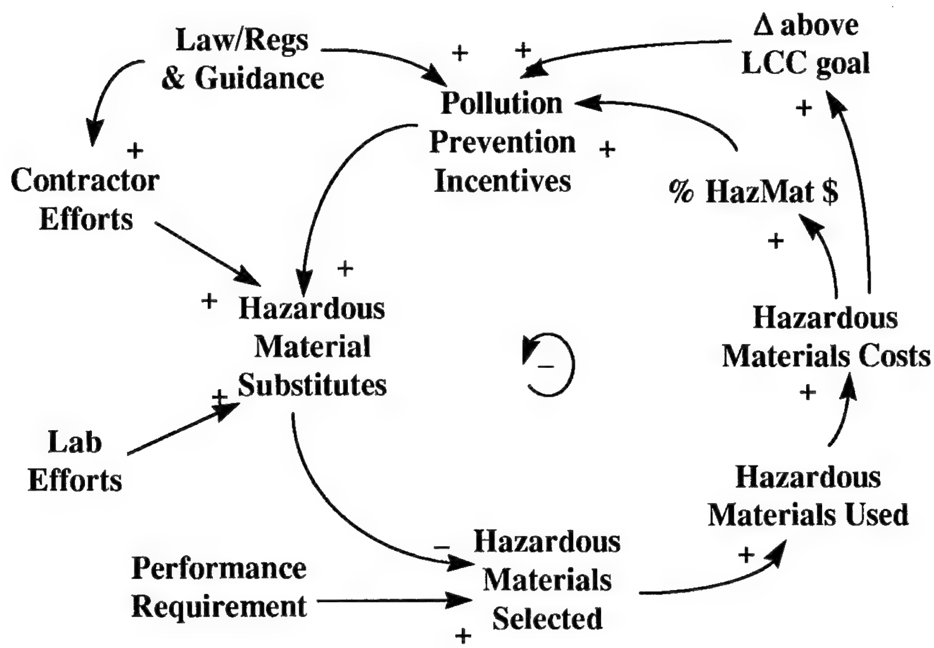


Figure 4: Top Level Influence Diagram

The Hazardous Materials Selected influence represents the number of hazardous materials selected during the design phase and recorded in drawings and other technical documents. The Performance Requirement influence represents the drive of performance requirements to cause the selection of hazardous materials. The Hazardous Materials Used influence accounts for the total number of hazardous materials intrinsic to the weapon system and used in manufacturing, operational maintenance, and depot repair of the aircraft. This influence also includes the waste generated from the use of hazardous materials. The Hazardous Materials Costs influence is the cost of using the materials represented in the Hazardous Materials Used influence. The Percent Hazardous Materials influence represents the fraction of the overall LCC costs that are attributed to the use of Hazardous Materials.

Influence diagrams are typically examined by assuming if all else is held constant, and the preceding influence increases, what is the effect on the following influence.

For instance, starting at Delta Above LCC Goal and going around to the left, if all else is held constant and the Delta Above LCC Goal increases, then the incentive to perform pollution prevention would increase in the hopes that pollution prevention efforts would reduce total system costs back towards the goal. So this is shown as a positive influence with a plus sign. Assigning signs to the influences continues around the feedback loop. If all else is held constant, and the Pollution Prevention Incentive increases, the number of Hazardous Materials Substitutes would increase. If the number of Hazardous Materials Substitutes increases, the number of Hazardous Materials Selected would decrease (as represented by the minus sign). If the number of Hazardous Materials Selected were to increase, the number of Hazardous Materials Used in the system would also increase, which would increase the Hazardous Materials Costs. If the Hazardous Materials Costs increase, then both the Delta Above LCC Goal would increase and Percent Hazardous Materials Cost would increase. Finally, to complete the feedback loop, if Percent Hazardous Materials Cost increases, Pollution Prevention Incentives would increase.

Since there is an odd number of negative influences in this feedback loop, it is considered a negative or stabilizing feedback loop. This means that as more hazardous materials are selected and used, the percentage cost of hazardous materials and overall LCC increases; however, the system is designed so these increases in cost activate pollution prevention incentives that reduce the amount of hazardous materials needed to build or maintain an aircraft. In turn, this should lower the costs. Therefore, the behavior of this feedback loop is self-correcting, and as with all other negative feedback loops, its behavior is goal seeking. This means the feedback loop would continue to correct itself until it reached its goal or a point where

all the forces in the feedback loop were in balance. As represented in Figure 3, the delta between projected LCC and the LCC goal would start to grow, but then the system would work to bring this delta back down until a steady state was reached.

Model Description

The influences shown in Figure 4 were then coded into a system dynamics model. The components of that model are discussed below. Instead of showing the more complex STELLA II ® coding diagrams, simplified flow diagrams are used to help depict the functions of the different model components. The actual STELLA II ® flow diagrams and equations are contained in the Appendix.

Hazardous Materials Selection, Substitution & Use. The Hazardous Materials Substitutes influence, Hazardous Materials Selected influence, and Hazardous Materials Used influence shown in Figure 4 are all represented in the Hazardous Materials component of the model shown in Figure 5. The Hazardous Materials Selected is a function of substitution efforts working to eliminate hazardous materials, while performance requirements drive the use of hazardous materials. Because performance requirements often drive the use of hazardous materials (for example, environmentally friendly, water-based materials often have excessive drying times), it is difficult to optimize both performance requirements and non-hazardous substitutes. Therefore, these values in the model are viewed as opposing forces and are subtracted from each other. Successful substitution efforts are dependent on both the existence of a non-hazardous substitute and knowledge that the substitute exists. The ESH requirements were added later at the suggestion of ASC/EMV as another influence that works to limit the selection and use of hazardous materials.

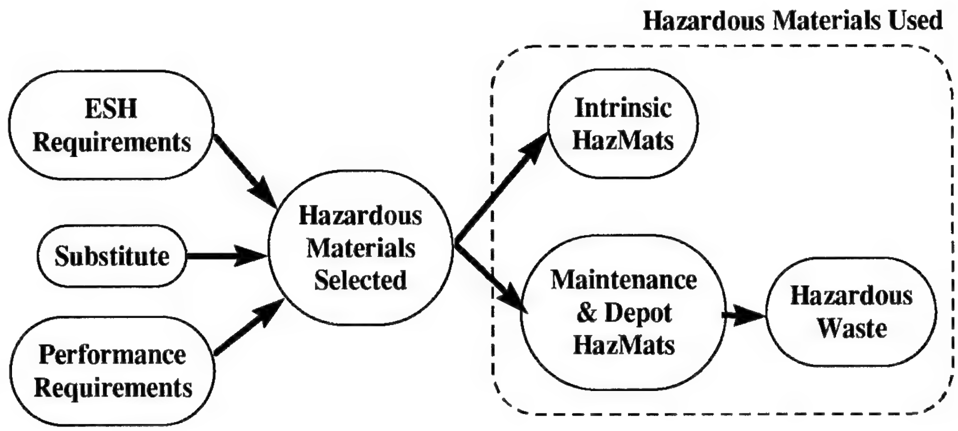


Figure 5: Hazardous Materials and Waste Relationships

The Performance Requirement influence is represented as a soft variable ranging from zero to one. A Performance Requirement of one would represent a very high performance system, which would drive a high use of exotic or hazardous materials. The substitution influence also ranges from zero to one (with one as the maximum substitution effort) and is the summation of the contractor efforts, Air Force Research Laboratory efforts, Air Force SPO efforts. These influences are covered further in the Pollution Prevention Incentive model component described below. Typically, the fact a substitute exists is not sufficient. This knowledge must be shared among the contractors or SPOs; in other words, in addition to having a substitute material available, there must be knowledge that the substitute exists. As the Systems Engineering Efforts, Contractor Efforts, and Substitution influences increase, the Substitution Knowledge influence value increases from zero to one (with one as maximum knowledge). It is assumed the Systems Engineering Efforts, Contractor Efforts, and Substitution influences all contribute equally to the Substitution Knowledge influence. The ESH Requirements also ranges from zero to one (with one as the maximum avoidance of hazardous materials) and is driven by the Policy and

Law/Regulations influences. It is assumed these two influences are of equal weight in influencing the ESH Requirements.

The Hazardous Materials Used influence shown in Figure 4 is represented in the model by three main entities; hazardous materials used in maintenance and depot actions, hazardous materials intrinsic to the system, and hazardous waste generated from the use of hazardous materials. These are shown within the dotted line Hazards Materials Used section of Figure 5. It is assumed the more hazardous materials that are selected, the more hazardous materials are intrinsic to the unit and the more hazardous materials are required for maintenance and depot actions. The hazardous materials use can further be increased because the same material can be used in multiple tasks or becoming intrinsic in multiple units. This influence is further multiplied by the number of units currently available in the inventory. Once the hazardous material is selected for use in a maintenance or depot action, a certain percentage of it becomes a hazardous waste that must be dealt with. The hazardous waste from maintenance and depot actions is calculated by using a factor to convert maintenance hazardous materials into hazardous wastes. This represents the fact that not all maintenance material becomes a waste.

The model is designed so hazardous materials are only chosen during the CE, PDRR, and EMD phases, while the number of hazardous materials in the system can be reduced over the rest of the life cycle through substitution efforts, allowing up to ten pollution prevention changes per year. This is based on the average number of substitutions the author has observed a year while working PDRR and EMD on a fighter program. The parameters that are entered directly into the model, instead of being calculated by the dynamics of the model, are listed in Table 1. The performance

requirement of 0.8 would represent a high performance system, such as a super sonic fighter with low observable technology, which would drive a higher hazardous materials use. The 1000 maintenance acts per year is an estimate based on the fact that high performance fighters have approximately 7000 maintenance acts total, but many of these actions, such as repairs and painting, do not take place every year or on every unit. The 20% conversion of hazardous materials to hazardous waste is just a rough estimate. Actual values would depend on the process, but may be lower overall due to process improvements.

Table 1: Hazardous Material Selection Parameters

Name	Value	Range
Maintenance Act/Unit/Year	1000	0 - ∞
Waste Converted to HazMat	20%	0-100%
Performance Requirements	.8	0 - 1.0

Hazardous Material Costs. For clarity, the Hazardous Materials Costs influence shown in Figure 4, is represented in two components of the model; the Hazardous Materials Cost component and Hazardous Waste Cost component. To simplify the model, instead of considering all seven entities that account for 94% of the hazardous materials and waste costs, only the four entities of disposal, liability, PPE, and procurement (which captures 81% of their costs) were used in the model. Of these four major cost categories, the cost of procuring the hazardous materials, liability associated with a hazardous material, and the cost associated with PPE are accounted for in the Hazardous Materials Cost influences shown in Figure 6. The cost of waste liability and disposal are reflected in the Hazardous Waste Cost component.

The procurement cost for the hazardous materials occurs in manufacturing, depot, and maintenance (for the propose of this project, maintenance includes both operations

and support activities). The manufacturing hazardous material cost is a function of the number of hazardous materials used to manufacture a unit, the production rate, and the cost per hazardous material. This cost would represent the cost to procure and transport the material. The Depot hazardous materials cost is a function of the number of units at the depot and the hazardous materials used to overhaul and repair each of these units. It is assumed the depot cycle for a unit is every five years, so after the first five years, each manufactured lot of units returns to the depot and continue returning on a five year cycle. Units are not returned to depot if they are within five years of the end of their twenty year life cycle.

The PPE cost considers both the cost of the PPE and the time loss due to the reduced work efficiency caused by wearing PPE. This is similar to current cost models that add repair time to account for the added effort involved in using hazardous materials (DeBanto, 1997). The cost of the PPE could be dropped from the model due to its low impact to the overall cost and the wide range of uncertainty in estimating cost and usage of the PPE. The maintenance cost of hazardous materials is a function of the maintenance acts performed on a unit each year and the overall number of units deployed.

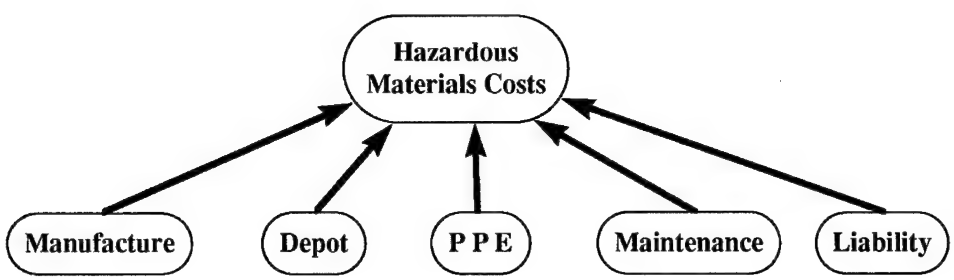


Figure 6: Hazardous Materials Costs Relationships

The Liability Cost was assumed to increase the more hazardous materials were used. The hazardous materials cost parameters that are entered directly into the model, instead of being calculated by the dynamics of the model, are listed in Table 2.

The Cost of Hazardous Material is an estimate that represents the cost for each use of a hazardous material. The Cost of PPE is an estimate since costs would vary widely ranging from protective gloves to full body suits with forced air respirators. Base pharmacies were hesitant in giving estimates since the range was so large. PPE Used per Hazardous Material is an attempt to acknowledge that PPE can be reused. The PPE Time Penalty factor is multiplied by the number of hazardous material uses calculated by the model so that the actual PPE Time Penalty increases with the number of hazardous material uses. The overall PPE Time Penalty in the model is around 2% (of the operational costs), which is close to the factor used in other hazardous materials LCC models.

Table 2: Hazardous Materials Cost Parameters

Name	Value	Range
Cost per HazMat/Use	$500	0-∞
Cost of each PPE	$500	0-∞
PPE used per HazMat	.75	0-1
PPE Time Penalty	~ 2%	0-10%

The Hazardous Waste Cost component of the model is shown in Figure 7 and addresses the disposal costs for the hazardous waste that occur in manufacturing, depot repairs, and maintenance. It also addresses the liability of hazardous waste and the disposal costs of the entire units (including hazardous waste disposal) at the end of the unit's life cycle. The Manufacturing Hazardous Waste Cost is a function of the amount of hazardous waste generated per unit manufactured, the production rate,

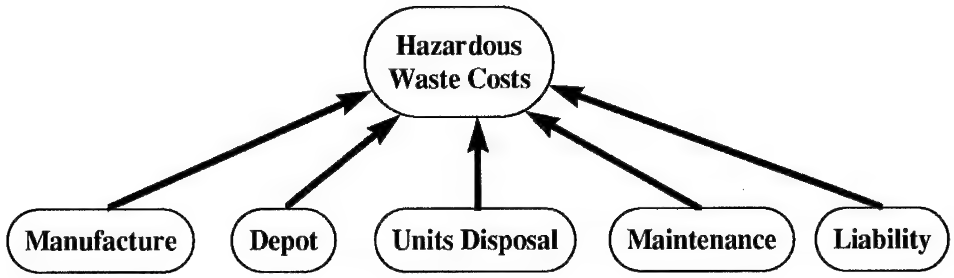


Figure 7: Hazardous Materials Costs Relationships

and the cost of the hazardous waste generated by the manufacturing process. The Depot Hazardous Waste Cost is a function of the number of units at the depot and the hazardous waste generated during the overhaul and repair of each of the units. Again, it is assumed the depot cycle for a unit is every five years, so 20% of the units must be returned to the depot each year. The maintenance cost of hazardous waste is a function of the maintenance acts performed on a unit each year and the overall number of units deployed. The Liability Cost was assumed to increase the more hazardous waste was generated. The hazardous waste cost parameters that are entered directly into the model, instead of being calculated by the dynamics of the model, are listed in Table 3. The Cost of Hazardous Waste Disposal represents the costs of disposing of waste generated from each use of a hazardous material. Depot Actions per Unit

Table 3: Hazardous Waste Cost Parameters

Name	Value	Range
Cost per Haz Waste/Use	$1000	0-∞
Depot Action per Unit/Year	1000	0-∞

represents the number of depot actions performed on the units at the depot in one year. It is based on the fact that higher performance fighters have approximately 2000

depot actions, but these acts are not performed on every unit every time it is returned to the depot.

The maintenance cost of hazardous waste is a function of the maintenance acts performed on a unit each year and the overall number of units deployed. The manufacturing, depot, and maintenance hazardous waste costs represent the cost for treatment, collection, handling, permits, licenses, analysis, and disposal of the hazardous waste. The cost for unit disposal is based on two influences; the cost for disposal of the unit, and the cost to remove any hazardous wastes from the unit before it is demilitarized. Using a rule of thumb discussed earlier, the disposal cost of a unit is calculated so that the cost of disposing of all the units equals 10% of the total LCC costs. The cost of removing hazardous materials from the unit is a function of the number of hazardous materials intrinsic to the unit and the cost to dispose of these hazardous materials. The Liability Cost is assumed to increase as more hazardous waste is generated.

Percent Hazardous Materials Cost. The Percent Hazardous Materials Cost influence shown in Figure 4 is calculated by adding the projected hazardous materials and projected hazardous waste costs and dividing by the projected LCC. The projected hazardous materials, hazardous waste, and LCC cost calculations are explained later. A simplified representation of LCC is used in the model to calculate total system cost to date. Since pollution prevention costs need to be highlighted, the cost of pollution prevention changes, hazardous materials costs, and hazardous waste costs are listed separately. The rest of the total cost to date are represented by research and development (R&D) costs, investment costs, operational costs, and disposal costs. As

shown in Figure 8, the Total Cost To Date is a summation of all these different costs at any given time during the system's life cycle.

The R&D phase of the program, which includes CE, PDRR and EMD, is assumed to last for a total of ten years with total costs summing to 10% of the final overall LCC. For simplification, the cost is assumed to be constant each year. The Investment cost, which includes production and deployment, is calculated to equal 30% of the final overall LCC. It is based on the cost per unit and the number of units produced. The

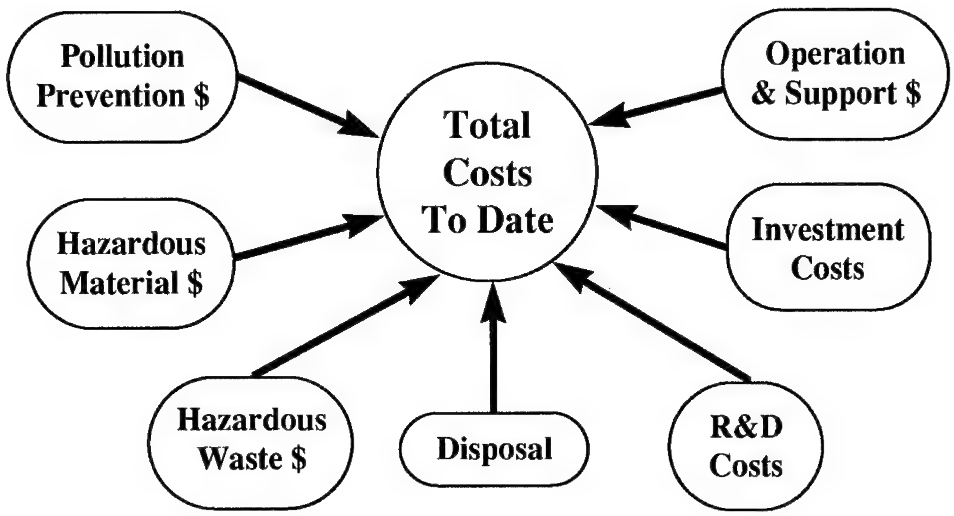


Figure 8: Life Cycle Cost Relationships

operational cost is defined as 50% of the final overall LCC, is calculated on a per unit basis, and is multiplied by the number of units in inventory. The number of units in inventory is controlled by the Production Rate and the assumption of a twenty year life cycle. The Production Rate is zero for CE, PDRR, and EMD phases of the program (the first ten years) and then is 30 units per year over the next 10 year period. As the units are produced, they are assumed to stay in operation for twenty years before they are disposed. The disposal cost for the units (not including hazardous waste disposal costs) is calculated so that the cost for all the units is 10% of the overall LCC.

Pollution prevention change costs are based on the cost per change and the number of pollution prevention changes per year. The cost of pollution prevention changes is modeled to increase over time and to reflect the increased cost in making changes after the design becomes more and more solidified. Preliminary work on pollution prevention fund estimating indicates that extremely complex or difficult non-hazardous material substitution efforts could cost as much as $5 million (AFMC, 1994:17). This is used as the maximum pollution prevention change cost. The change per year is modeled to decrease over time so fewer and fewer changes are incorporated after the system design is moved into production and eventually fielded. As mentioned earlier, the maximum number of pollution prevention changes per year is ten. The exact number is determined by the model as a function of the Air Force pollution prevention efforts and the pollution prevention Change Rate. Finally, Pollution Prevention Changes are only implemented if they provide a cost savings.

The cost savings is determined by comparing the current cost of implementing a pollution prevention change with the net present value of the costs the pollution prevention change would save over the remainder of the program's life cycle. To calculate the cost saved by eliminating a hazardous material, an estimate of the cost of each hazardous material used is calculated by averaging the total projected hazardous materials cost and projected hazardous wastes cost across the total number of hazardous materials projected for selected. It is assumed the total cost is avoided if the hazardous materials use is eliminated. There is a cost savings if the net present value of the cost saved by eliminating a hazardous material is greater than the cost of implementing the change. If there is not a cost savings, the pollution prevention change is not implemented. For simplicity in the model, it is assumed all pollution

prevention changes immediately take effect on all fielded systems. There are no parameters in the Total Cost To Date model component that are entered directly into the model; they are all calculated by the dynamics of the model

Pollution Prevention Incentives. The Pollution Prevention Incentive influence shown in Figure 4 is affected by the Contractor, Air Force SPO, and Air Force Research Laboratory pollution prevention efforts. Figure 9 depicts how the Hazardous Material Substitution influence is driven by contractor pollution prevention efforts, Air Force SPO pollution prevention efforts, and Air Force Research Laboratory pollution prevention efforts. These are represented in the model as soft variables ranging from zero to one, with one as the highest incentive to perform pollution prevention efforts.

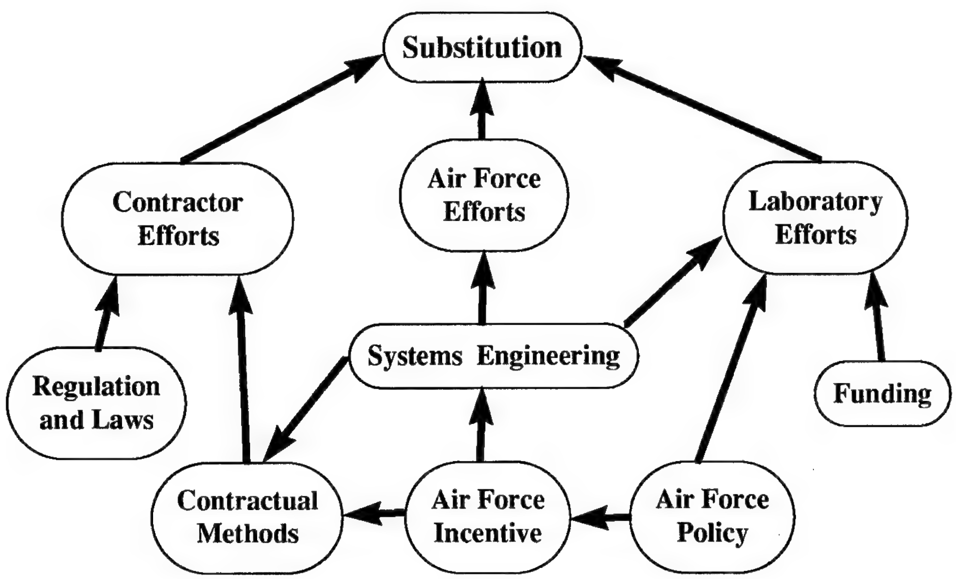


Figure 9: Non-Hazardous Materials Substitution Relationships

Contractor pollution prevention efforts are driven by laws and regulations that control the manufacturing process and they are also driven by contractual methods for which the Air Force SPOs pays. Policy does not directly affect the contractor's pollution prevention efforts; its effects are translated through the SPO's contractual vehicles to

the contractor. Contractual Methods, such as statements of objective, contracts, and source selection standards are influenced by Air Force pollution prevention incentives and the effectiveness of pollution prevention in the systems engineering process. Both these influences affect the overall effectiveness of integrating pollution prevention into the contractual process, and either influence could independently maximize Contractual Methods.

Air Force SPO pollution prevention efforts are implemented through the systems engineering process and are primarily affected by how incited the program manager is to integrating pollution prevention into the systems engineering process. Pollution prevention efforts in the systems engineering process are driven by Air Force incentives to perform pollution prevention. The higher the incentive to perform pollution prevention, the more pollution prevention is integrated into the systems engineering process. For the purpose of this model, the CE, PDR, and EMD effects of hazardous material trade studies are aggregated into the Pollution Prevention in Systems Engineering influence.

The Air Force Research Laboratory pollution prevention efforts represented in Figure 9 are primarily influenced by the ESOH TIPT process mentioned earlier. Input to the ESOH TIPT process is accomplished as pollution prevention needs are identified by the SPO's systems engineering process. To some extent the Air Force Research Laboratory's pollution prevention efforts are also influenced by Air Force Policy. An example of Air Force policy driving laboratory efforts is the laboratory's substitution efforts for the ozone depleting chemical fire suppressant Halon. This was primarily driven by the Air Force's policy to eliminate Halon from weapon systems instead of stockpiling future supplies of Halon. In this project, the Air Force Research

Laboratory's pollution prevention effort ranges from zero to one and is affected by Policy Influence and the Pollution Prevention in Systems Engineering Influence. Since ample funding of all ESOH TIPT projects is not feasible, the influence of the Air Force Research Laboratory's pollution prevention influence is degraded using a fraction funding factor that reduces the overall influence.

Figure 10 shows how the Air Force incentive to perform pollution prevention is driven by three main factors; laws and regulations, policy, and financial influences. In the model, each of these influences is tempered with a factor that represents how efficient the influence is in driving pollution prevention. The financial driver to perform pollution prevention is based on two influences. One influence is the ratio of Hazardous Material and Hazardous Waste costs to the overall cost of the system. As this ratio approaches 10%, the financial aspects of the program drive a maximum

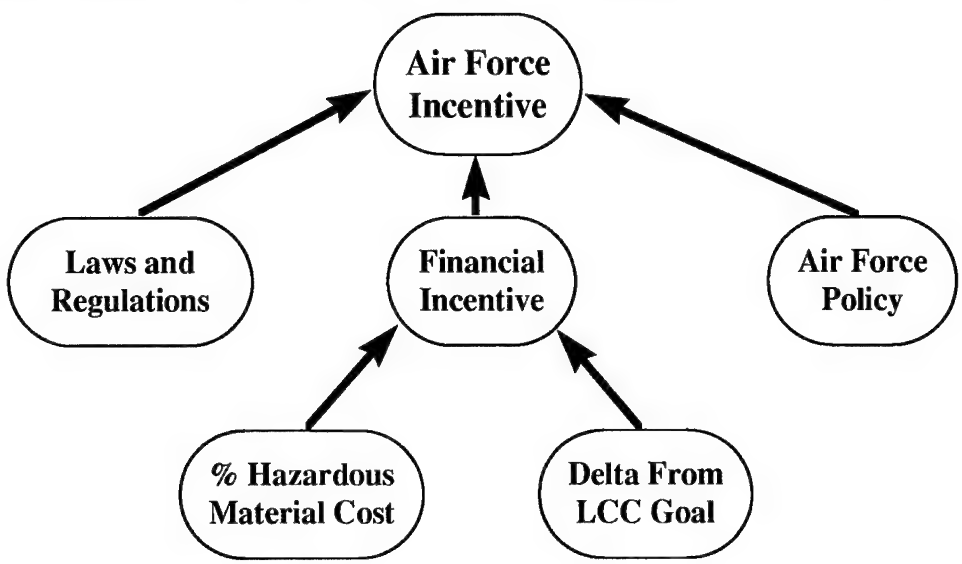


Figure 10: Air Force Pollution Prevention Incentives

pollution prevention effort. The other influence is how much the projected LCC differs from the program manager's LCC goal. Either one of these influences may drive the financial incentive to its maximum value of one.

The model is designed so that the Air Force's and contractor's ability to introduce pollution prevention changes decreases over time, as the systems design matures and as the disposal phase of the program is reached. This influence is called the Pollution Prevention Change Rate and is a soft variable with the range from one to zero (with one representing the maximum ability to change). It is used as an efficiency factor in the Air Force and Contractor Pollution Prevention Efforts influences. The pollution prevention Change Rate is at its maximum, one, at the beginning of the program, and approaches zero asymptotically as the end of the life cycle is neared.

The Pollution Prevention Incentive parameters that are entered directly into the model, instead of being calculated by the dynamics of the model, are listed in Table 4. The Lab Funding Factor is an estimate and is used to reduce the efficiency of Air Force Research Laboratory efforts. The Policy and Law & Regulation variables represent the force behind these efforts. They are set at one to represent the requirement for the Air Force and contractors to meet the law and for the Air Force to meet policy. Their corresponding efficiency factors represent their effectiveness at initiating pollution prevention efforts. The ESH Efficiency Factor also represents the effectiveness of ESH actions to implement pollution prevention efforts. These efficiency factors are estimates derived from professional judgment.

Table 4: Pollution Prevention Incentive Parameters

Name	Value	Range
Lab Funding Factor	50%	0-100%
Policy	1	0-1
Laws & Regulations	1	0-1
Policy Efficiency Factor	0.5	0-1
Laws/Regs Efficiency Factor	0.7	0-1
Cost Driver Efficiency Factor	0.9	0-1
ESH Efficiency Factor	0.5	0-1

Projected Cost. Part of measuring the delta between the LCC goal and the projected LCC requires projecting the costs of the system from the present data out to the end of the system's life cycle. To do this, the current rate of selecting hazardous materials is projected to the end of the EMD phase to estimate the following: future amounts of hazardous materials used in maintenance and depot actions; future hazardous materials intrinsic to the system; and future hazardous waste generated from the use of hazardous materials. Also, projected Hazardous Material Costs and Hazardous Waste Costs must be calculated. For depot costs, the total number of all the depot trips all the planes make to the depot is calculated as Remaining Depot Unit Trips. Future depot expenses are calculated by multiplying depot expenses by the total number of remaining depot trips. Future remaining manufacturing expenses are calculated by multiplying the projected amount of hazardous material by appropriate costs and then by the projected production rates. The future maintenance costs of future units and future costs of maintaining existing units are calculated by multiplying the total number of " unit years" (the number of units times their remaining life times) by the maintenance expense per aircraft per year. All the costs up until the current date

are then added to the projected costs from the current date until the end of the program's life cycle. This provides an estimated LCC at the end of the program's life cycle.

Validation Results

Structural Verification. First, the structure and influences were developed from the influence diagram and compared to the mechanisms discovered during the literature review. Then, further structural verification was performed by comparing the actual structure of the model with the structure of the real world system. This revealed that the hazardous materials in the system needed to be considered intrinsic to the system, as materials used in manufacturing, maintenance, and depot operations, and as waste generated by the manufacturing, maintenance, and depot operations.

By explaining the detailed model structure to ASC/EMV personnel, they were able to ensure the model structure was reasonable, that there were no contradictions between the model and the real world system, and that the assumptions in the model were valid. The structure of the model was revised through an iterative process based on discussion with individual ASC/EMV personnel and a group presentation of one of the latter versions of the revised model.

Parameter verification. Parameter Verification was conducted conceptually by reviewing the parameters with ASC/EMV, SPO, and ASC financial and logistic personnel to ensure the parameters encoded in the model actually existed and matched elements in the real system. Although the existence of the parameters was not refuted, Numerical Verification of the parameters' values and ranges was extremely difficult to accomplish. The reply from the AFMC Logistics Office when asked about

such rules of thumb as average waste generated from a hazardous material, number of manufacturing chemicals and operations that transition to use at the depot, and average cost of PPE per hazardous material was, "Looks like your searching for the same numbers everyone else is" (Campbell, 1997). Soft variables such as Performance Requirement, Policy Efficiency, and Laws/Regs Efficiency, were assigned using best judgment.

Other factors were discovered to lead to the uncertain parameter values. For instance, the parameter that represented the waste generated from the hazardous materials would vary greatly depending on the type of material and the media (air, land, or water) in which the pollution resided. Since PPE like face shields can be reused several times, while gloves may be reused only a few times, the PPE used per hazardous waste parameter could also vary widely. Values such as the cost of a hazardous material, or the cost of hazardous waste disposal also vary widely. The parameters for maintenance and depot acts per unit would also vary depending on the type and complexity of the aircraft. The effects of these uncertainties and variances were examined during sensitivity analysis.

Structural Adequacy. Structure Boundary Adequacy was validated by explaining to ASC/EMV personnel the aggregation of real world influences incorporated into the system dynamics model. They also reviewed the model to ensure all relevant structures had been included and that no plausible hypothesis could be proposed that indicated the need for additional mode entities or mechanisms. For example, the suggestion that a program manager bribe mechanism be added is not realistic, since this is not a plausible entity for this system. The Air Force Research Laboratory Influence on substitution efforts surfaced during this review process. This iterative

review process also introduced the Cost Savings component of the model and the ESH Requirements Influence, which affects the hazardous materials selected.

Behavior Boundary Adequacy ensures the boundary of the system includes all the necessary mechanisms. This was verified by ensuring the addition or removal of model structure did not affect the model's behavior. Corporate image was suggested by ASC/EMV personnel as an additional component to the pollution prevention incentive. However, adding this structure did not significantly affect the model. It was decided this is typically driven at an Air Force level through Air Force policy, and is represented in the model through the Air Force Policy influence. Initially, the Cost Savings mechanism of the model seemed to be an excessive structure. Because the life cycle cost savings of pollution prevention efforts were so large, this mechanism never switched off until the very end of the model's life cycle. However, this structure was left in the model to ensure adequate model response to policy scenario testing. The effects of exponential smoothing can be seen in Figure 11. Exponential smoothing was used to obtain a more accurate value for Projected Hazardous Materials Selected. This structure was left in the model, because its removal caused excessive Projected LCC values..

Extreme Conditions. The model's behavior under extreme conditions was tested by setting the stocks and rates to realistic real world extreme conditions and observing the behavior of the model. It was important that the model did not crash or that the responding behavior seemed realistic and was explainable. It was discovered that setting the Hazardous Material Selected Stock to zero causes an error in the model

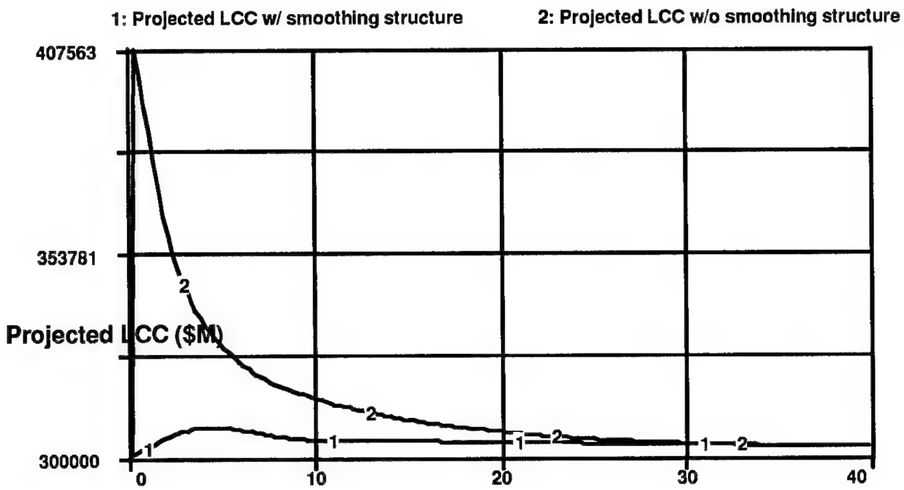


Figure 11: Behavior Boundary Adequacy for Exponential Smoothing

because the model then attempts to divide by zero in the cost savings component. To prevent this from happening, it was assumed that at least one hazardous material is selected for use in the system, so the initial value of this stock was set at one. Sometimes setting variables to extreme conditions was used to verify certain portions of the model were working. Table 5 summarizes results from extreme condition testing when all the pollution prevention incentive influences were set at zero, then one influence at a time as allowed to operate at it's maximum value.

Table 5: Pollution Prevention Incentives Extreme Condition Testing

Influence	Final LCC To Date
No Pollution Prevention Efforts	$339,096 M
Policy Influence Only	$309,667 M
Financial Incentive Influence Only	$309,667 M
Law & Regulation Influence Only	$302,635 M
All Influences at 100%	$302,253 M

Using the current default settings in the model, the final LCC is $302,550 M; however with no pollution prevention efforts, the overall final LCC is over 10% higher.

Activating either the Policy influence or the Financial Incentive influence to their maximum value allows the Air Force Pollution Prevention Efforts influence to operate at its maximum value, which accounts for the identical final LCC values in Table 5. The reason the Law & Regulation influence is more successful at controlling LCC is because it influences both Air Force and Contractor Pollution Prevention Efforts simultaneously, so the overall substitution efforts in the model are maximized. Activating all influences does not drive a significantly lower LCC than the Law & Regulation influence extreme condition, because Air Force and Contractor hazardous material substitution efforts are already at their maximum level. The slight decrease in overall LCC is due to increased Air Force laboratory efforts.

Behavior Anomaly. Behavior anomalies, such as stocks or rates remaining constant or changing erratically during the model simulation, were observed during the initial coding and running of the model. This often indicated the model needed revision so it more accurately reflected the mechanisms of the real world system. It also indicated that inconsistent units had been added together, such as adding a unitless soft variable ranging from 0.0 - 1.0 to a dollar amount ranging from $0-500 million or numbers of hazardous materials. The units of all equations were carefully checked to ensure they were consistent. The model was also tested to see if it showed implausible behavior when the assumptions are altered.

Surprise Behavior, an unnoticed behavior of the real life system, was not discovered during testing. Any behavior thought to be Surprise Behavior was generated due to errors in the model, which actually made it a Behavior Anomaly. These errors were corrected in the model.

Reference Mode Comparison

Comparison of the model output shown in Figure 12 with the hypothetical reference mode shown in Figure 3 indicates a reasonable match to the projected behavior. At the beginning of the program, projected costs are high because of the projected rate at which hazardous materials are being chosen for the system. As the pollution prevention mechanism is activated, the rate at which hazardous materials are selected is reduced, which in turn reduces the projected LCC. Projected costs continue to decrease during the life cycle of the weapon system. The decrease becomes smaller in the latter portion of the life cycle because the ability to perform pollution prevention efforts is inhibited by the solidification of the design over time and the decreased potential to achieve a life cycle cost savings, due to the decrease in the program's remaining life (there is less time to achieve a cost savings).

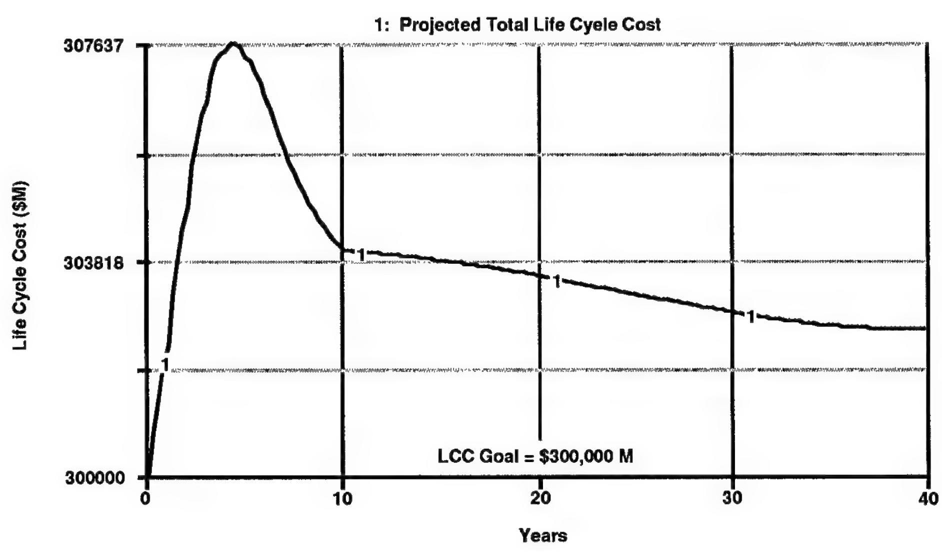


Figure 12: Reference Mode Comparison

Sensitivity Analysis

Typically in system dynamics models, the sensitivity of critical parameters is tested to see how they affect the model's outcome. Because, in this particular model, the criticality of the parameters is unknown, and the ranges of the parameters are unknown or contain uncertainty, all of the parameters were tested for sensitivity to observe how much they affected the outcome of the model. Parameters were varied one at a time across their entire possible range and their overall affects on the system were observed.

The sensitivity testing for the Hazardous Material Selection component of the model, and the change in overall LCC are shown in Table 6. The change in Maintenance Acts Per Unit has a greater effect on LCC than changes in the Waste From Hazardous Materials ration. This makes sense because the hazardous waste available is always only a fraction of the total hazardous materials. It is interesting to note the change of the performance requirements soft variable from 0.8 to 1.0 shows a large increase LCC. This is due to the fact high performance drives a high use of hazardous materials, which in turn overcomes the system's ability to develop sufficient non-hazardous material substitutes.

Table 6: Sensitivity Analysis on Hazardous Material Component

Parameter	Run #1	Run #2	Run #3	Run #4	Run #5
Waste from HazMat	0.005	0.05	0.1	0.2	0.5
Life Cycle Cost ($ M)	302055	302169	302296	302550	303313
Maintenance Acts/Unit/Yr	1000	2500	4000	5500	7000
Life Cycle Cost ($ M)	302550	305956	309362	312769	316175
Performance Requirement	0.0	0.2	0.6	0.8	1.0
Life Cycle Cost ($ M)	300002	300002	300093	302550	313064

The sensitivity of the parameters for the Pollution Prevention Incentive component of the model were then tested. The results are shown in Table 7. Varying the Air Force Research Laboratory funding factor has little effect on the LCC. Lowering the Policy Efficiency influence from 1 to 0 has a moderate effect on the overall LCC, while lowering the Laws and Regulation Efficiency from 1 to 0 LCC cost significantly. The sensitivity of the Laws and Regulation Efficiency is due to the fact that it affects both contractor and Air Force efforts. Changing the Financial Driver Efficiency influence has little affect on the LCC because the current settings of the Laws & Regulations and Policy Influence Efficiencies are high enough to compensate for any reduced efficiencies of the Financial Driver Efficiency. The ESH Regulation Efficiency is fairly sensitive because it directly affects the hazardous material selection process and is not implemented or transformed through Air Force or contractor efforts.

Table 7: Sensitivity Analysis on Pollution Prevention Incentive Component

Parameter	Run #1	Run #2	Run #3	Run #4	Run #5
Funding Factor	0.0	0.25	0.50	0.75	1.0
Life Cycle Cost ($ M)	302746	302643	302550	302457	302365
Policy Efficiency	0.0	0.25	0.50	0.75	1.0
Life Cycle Cost ($ M)	305200	302988	302550	302550	302550
Laws & Reg Efficiency	0.0	0.25	0.50	0.75	1.0
Life Cycle Cost ($ M)	313637	307467	303424	302501	302439
Financial Driver Efficiency	0.0	0.25	0.50	0.75	1.0
Life Cycle Cost ($ M)	302550	302550	302550	302550	302550
ESH Efficiency	0.0	0.25	0.50	0.75	1.0
Life Cycle Cost ($ M)	311200	306819	302439	300861	300269

The sensitivity of the parameters for the Hazardous Materials Cost component of the model were tested. The results are shown in Table 8. Varying the Cost of Hazardous Materials/Use parameter did not significantly effect the overall LCC. Also, varying the cost of PPE or the amount of PPE used with each hazardous material did not significantly affect the LCC. However, changing the PPE Time Penalty parameters

Table 8: Sensitivity Analysis on Hazardous Materials Cost Component

Parameter	Run #1	Run #2	Run #3	Run #4	Run #5
Cost/HazMat	$50	$100	$500	$1000	$2000
Life Cycle Cost ($ M)	302139	302185	302550	303007	303919
PPE Time Penalty	.01%	.1%	1.0%	5.0%	10.0%
Life Cycle Cost ($ M)	301206	301328	302555	307981	314770
PPE per HazMat	0.1	0.25	0.50	1.00	2.00
Life Cycle Cost ($ M)	302374	302415	302482	302618	302890
Cost/PPE	$50	$100	$200	$500	$1000
Life Cycle Cost ($ M)	302349	302387	302550	302754	303161

had a significant effect on the LCC. This is due to the fact that the PPE Time Penalty cost is calculated as a fraction of the overall operational and support costs, which are fairly substantial and account for approximately 50% of the entire LCC.

The sensitivity of the parameters for the Hazardous Waste Cost component of the model were then tested. The results are shown in Table 9. Sensitivity analysis was not performed on the depot cycle time because it was treated as a constant number in order to calculate the number of trips to the depot remaining for the fielded units. Also sensitivity analysis was not performed on the disposal cost of the unit (not including hazardous material removal) because unit disposal cost is a function of the overall LCC

goal, which does not change and is set at the beginning of the program. The LCC is not sensitive to changes in the remaining depot parameters.

Table 9: Sensitivity Analysis on Hazardous Waste Cost Component

Parameter	Run #1	Run #2	Run #3	Run #4	Run #5
Cost Haz Waste/Use	$100	$200	$1000	$2000	$4000
Life Cycle Cost ($ M)	302378	302397	302555	302741	302123
Depot Action per Unit	500	700	1000	1500	2000
Life Cycle Cost ($ M)	302436	302482	302550	302664	302778

The rank order of parameters that had the most affect on the overall LCC are shown in Table 10. The significance of these sensitivity testing results and the insights this system dynamics project provided into the acquisition pollution prevention process is discussed in Chapter 5.

Table 10: Rank Order of Parameter Sensitivity

Parameter	Overall Δ in LCC	% Change in LCC
Maintenance Acts/Unit/Year	13625	4.5
PPE Time Penalty Cost	13564	4.5
Performance Requirements	13062	4.4
Laws & Reg Efficiency	11198	3.7

V Conclusions and Recommendations

Conclusion

This model examines the interaction of the pollution prevention process over the life cycle of a typical weapon system. Confidence was gained in the model by using system dynamics testing and validation procedures. The model's reproduction of the hypothetical reference mode behavior predicted in Figure 4 and the confidence gained in the model structure during standard system dynamics verification testing, verify that this project establishes a basic system structure for the perceived pollution prevention process in acquisition.

The sensitivity analyses indicate changes in the Maintenance Acts per Unit has one of the greatest impacts on overall LCC. This is logical, since the cost of hazardous materials and hazardous wastes related to a maintenance act is multiplied by both the number of units in the field and the number of years in the unit's life cycle. The time penalty associated with use of PPE also has one of the greatest impacts on overall LCC. This also makes sense because PPE increases the time required to perform operations and support tasks; this drives an increase in operations and support costs, which is the most expensive phase of the weapon system's life. Changes of the performance requirements soft variable had the next largest effect on LCC. This occurs because the need to obtain high performance drives a high use of hazardous materials, which in-turn overcomes the system's ability to develop sufficient non-hazardous material substitutes early in the weapon system's life cycle.

Although the top down application of laws and regulations across the acquisition process was thought to be an inefficient influence on the pollution prevention process,

the sensitivity analyses indicate laws and regulations have the next highest impact on pollution prevention reductions to LCC. However, this behavior is driven by the high effectiveness values assigned in the model, which assumes the ability of laws and regulations to directly address material substitution in the particular weapon system being modeled. In reality, this is not the case, since laws often set arbitrary limits for hazardous material, regardless of the amounts used on or cost incurred by the individual weapon system.

Given that laws drive a command and control approach to pollution prevention that is not efficient in reducing LCC, it can be assumed the overall real life efficiency of the law influence is less than one. During extreme condition testing, when the model's law influence is set at zero, the financial incentive and policy influences are still able to significantly reduce the LCC. Because this concurs with the current mental view of how the pollution prevention acquisition system should operate, it provides further confirmation of the model structure. Therefore the model provides an adequate platform for further study of the pollution prevention acquisition process and it's parameters.

Despite these approximate parameter values, the model does provide basic documentation of the pollution prevention process in weapon system acquisition. This initial attempt of solidifying and documenting the mental map of the pollution prevention process should facilitate future discussion and refinement of the structure. The primary pollution prevention influences and mechanisms were refined during the iterative system dynamics process and are represented by the influence diagram in Figure 4. Interaction of these pollution prevention influences and mechanisms and their effects on the acquisition process are represented in further detail in Figures 5 through 10 and

can be seen in even greater detail by studying the STELLA II ® diagrams in The Appendix.

The model's ability to represent accurate reductions in LCC is limited by the degree to which the strength and effectiveness of the parameters and influences is unknown. Many of the parameters have a wide range of values because they are dependent on the pollution media (air, water, land), and the type of weapon system under consideration. In spite of these limitations, the model documents the pollution prevention acquisition process for further discussion and provides a platform of the systems structure for future individuals to develop a defensible rationale for an optimum pollution prevention management strategy.

This model represents the way pollution prevention influences should work in the acquisition process; however, during the literature review and discussion with expert personnel, some discrepancies were discovered. The financial driver of understanding overall LCC cost overruns receives much less visibility in the real system than the EVMS cost system that only tracks the cost of acquiring the weapon system. This means there is little accountability for making decisions that affect the overall LCC, therefore, the financial incentive to perform pollution prevention for LCC savings is not highly visible. The inadequacy of the EVMS as a pollution prevention incentive is what drove the comparison of the projected LCC to the goal LCC in the model, which more realistically represents an incentive to perform pollution prevention.

Current historical costing data and cost-based accounting techniques that track pollution prevention costs to a specific system are still lacking or just coming on board. This causes difficulty in estimating an average cost per hazardous material in production, maintenance, and depot operations. The practice of having pollution

prevention funding available for quick implementation is not followed, so pollution prevention must compete for this funding from other functionals during the design process. This could delay the implementation of substitution efforts, which is critical in the early years of the program, because changes are less expensive and can be made quickly. Also, as observed in real life and encoded into the model, there appears to be no feedback that couples the laws and regulations to LCC incentives.

Recommendations

Although the model's parameters must be further examined because they use perceived quantities which are not well defined, some general recommendations could be made based on the most sensitive parameters found in the model. Focusing pollution prevention efforts on materials used multiple times in maintenance acts, or materials that require the use of PPE that highly inhibits operational tasks, would be a most effective use of pollution prevention resources.

A better understanding of the influences of pollution prevention on the reduction of LCC could be obtained if better data was kept on specific pollution prevention and hazardous materials costs. Currently, depot or operational costs for multiple systems are only tracked at a base level. Implementing cost-based accounting, which can relate base level hazardous materials costs to the specific weapon system or process responsible for the material's use, would provided a better picture of pollution prevention cost savings opportunities. This would increase the incentive to perform pollution prevention because the weapon systems with fewer hazardous materials would be recognized as requiring less money to maintain. Also, better historical records that specifically list hazardous material costs for existing systems, would

provide a better picture of the pollution prevention cost savings that could be realized over the life cycle of a weapon system program. Better historical records on hazardous materials cost would also facilitate more accurate hazardous material LCC models that could predict hazardous material costs over an entire weapon system's life cycle. This would ultimately improve visibility into how decisions made early in the weapon system's life cycle affect hazardous material costs over the system's entire life cycle, which would provide an incentive for performing pollution prevention early in the system's life cycle.

More detailed and accurate records regarding hazardous material LCC tracking could be driven by changes in policy. Policy requiring total LCC be tracked as closely as the EVMS cost system currently tracks procurement costs would raise visibility of the system's projected final LCC. Policy requiring the review of overall system LCC more frequently than at every major milestone review would also raise final LCC visibility. Finally, future policy should require hazardous materials costs as a separate component of the overall LCC projection. Recognition of the magnitude of hazardous materials costs and what specific processes and materials are driving these costs should provide a powerful financial incentive for performing pollution prevention efforts.

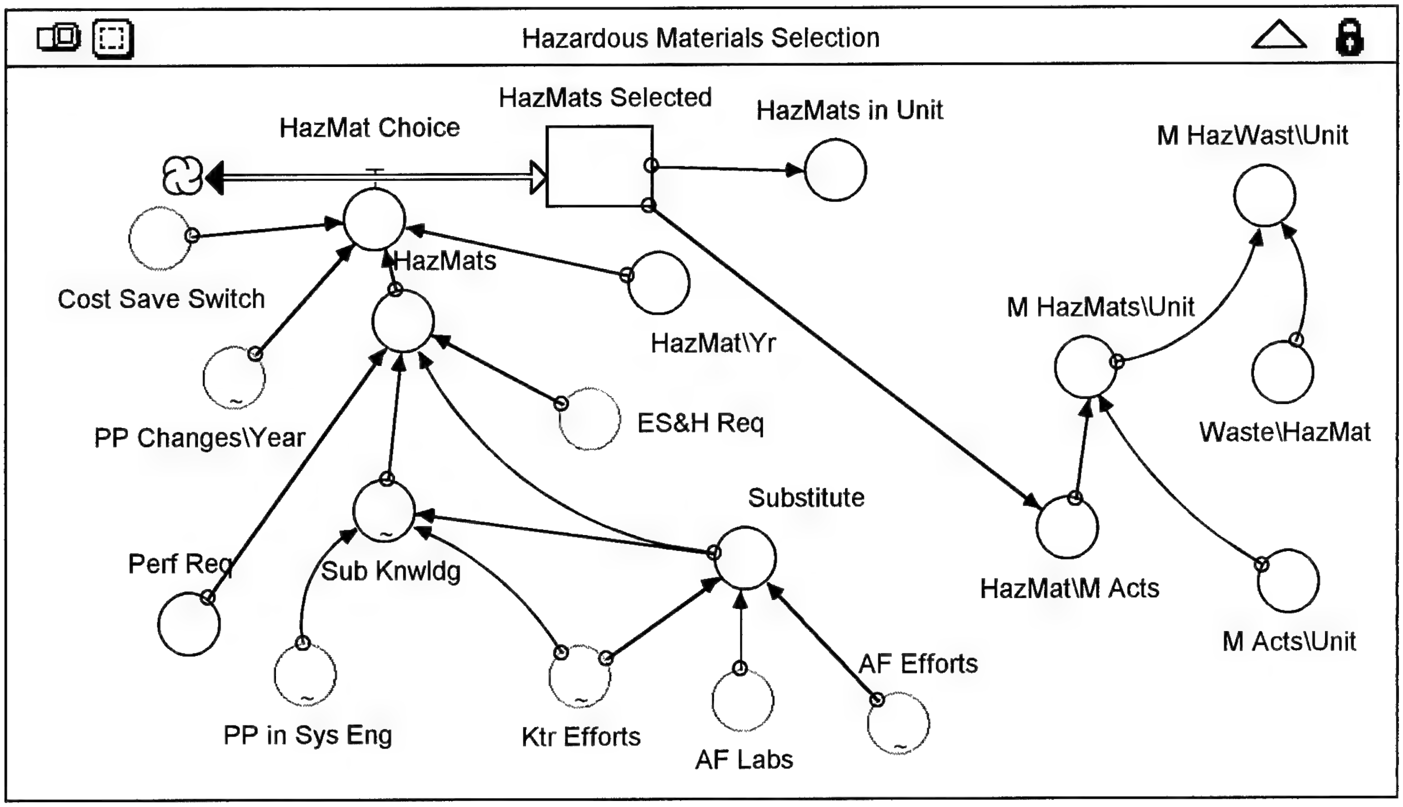
This model is the first step to better understanding of the pollution prevention acquisition process mental model. It is recognized that a combination of techniques must be used to successfully form a conceptual or mental model. The first step is to develop the initial conceptual model from literature and general insight. The second step is, with the model as an illustrative tool, to consult experts, possibly through the use of the Delphi questionnaire method. The third step is to hold an interactive Delphi workshop to further discuss the influences and workings of the model (Vennix and

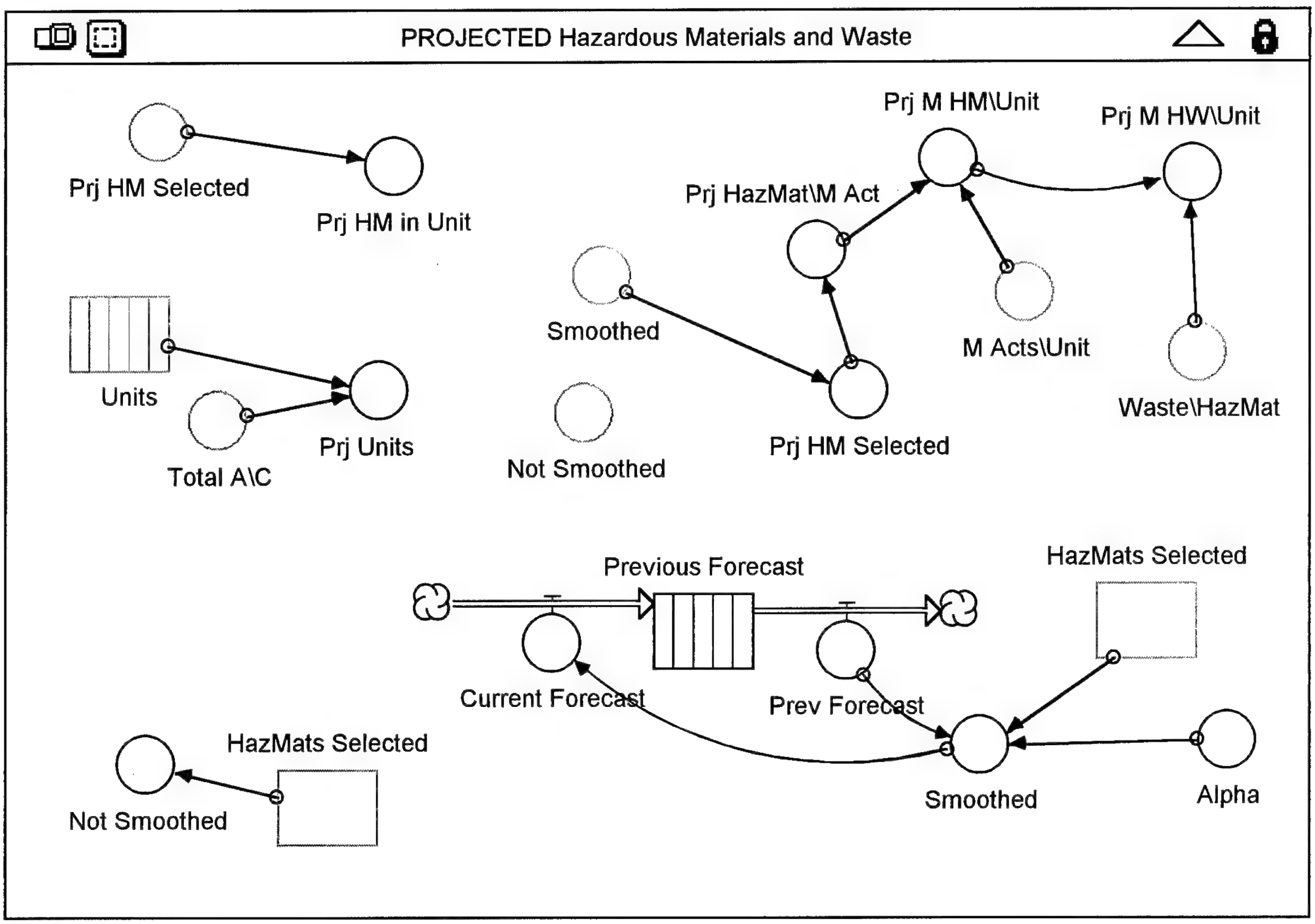
others, 1996:333). This project has accomplished the first step of identifying the basic model of the pollution prevention acquisition process. Further steps of refining the influences and parameters must now be accomplished by demonstrating the model to experts in the pollution prevention acquisition process and soliciting their feedback. An investigation into the effectiveness of Air Force Policies, Laws, and Regulations in implementing pollution prevention efforts should also be undertaken.

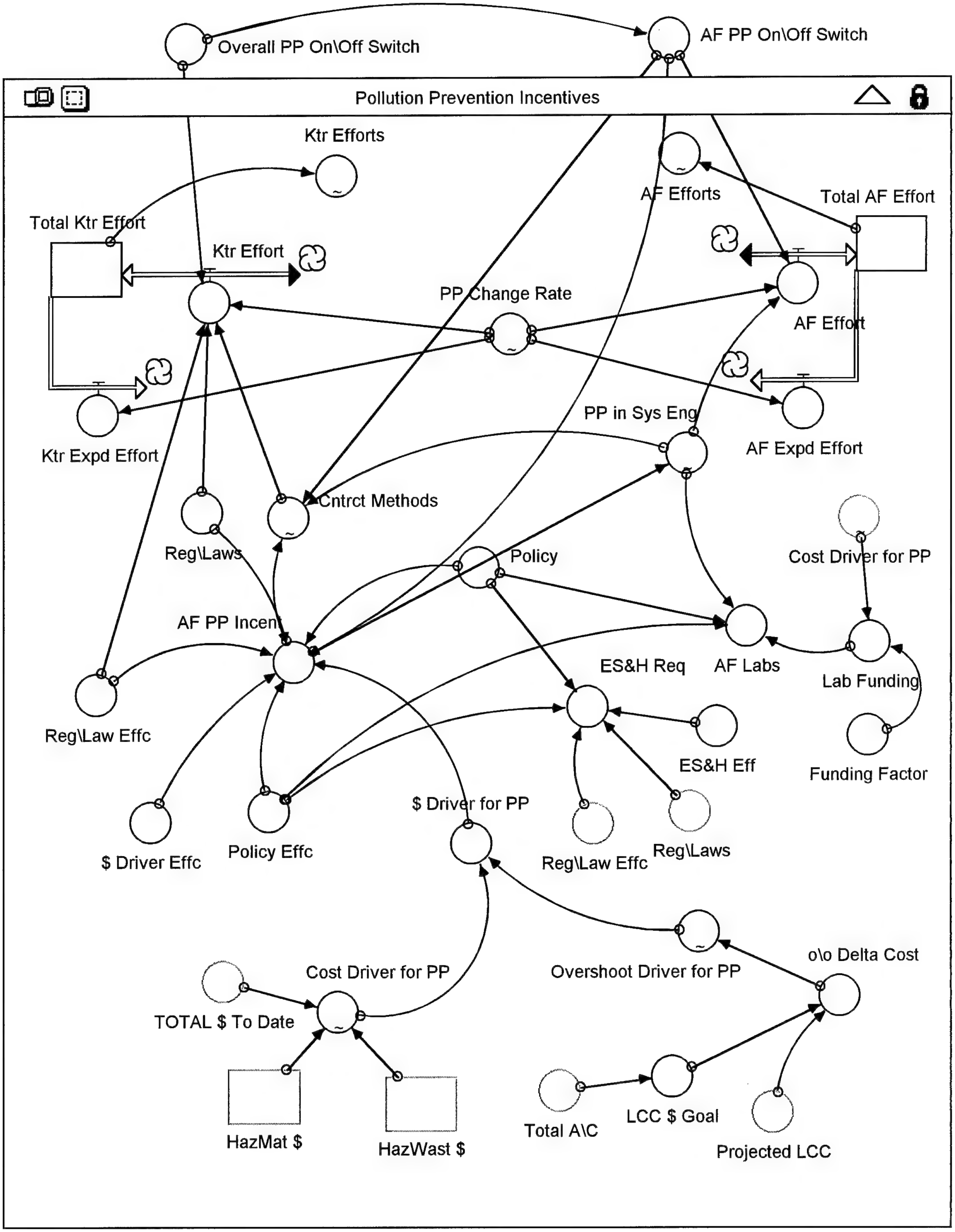
When working with the model in the future, the parameters must be further defined. Different weapon system acquisition programs consist of different levels of complexity which drives different performance requirements, system parameters and other variables. Future research efforts might investigate the possibility that a certain set of parameters better represents a bomber and another set of parameters better represents a fighter. Also, the effects of adding a delay in implementing pollution prevention changes could be added to represent the required time to obtain pollution prevention funding. Improved versions of the model would also allow for the tracking of multiple configurations of aircraft through the system. This would more realistically represent the effect of implementing pollution prevention changes in blocks, instead of assuming instantaneous implementation throughout the fleet.

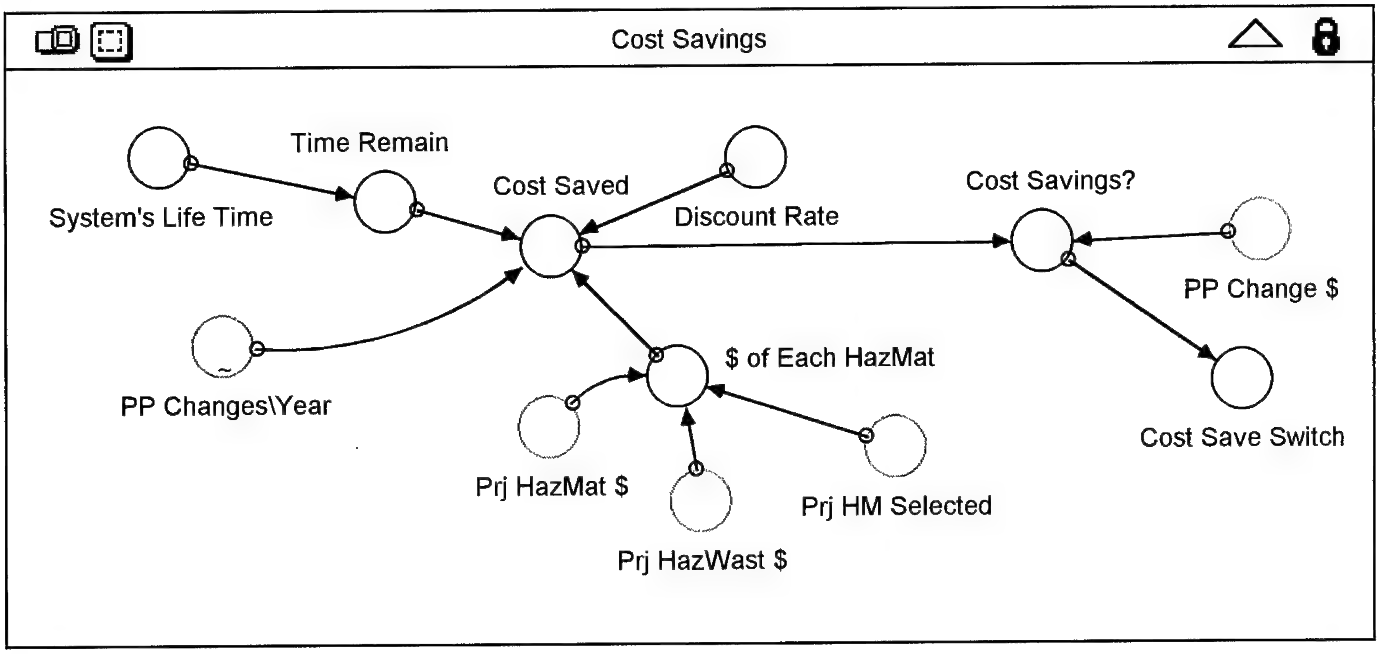
Also in the future, more environmental cost data may be available to incorporate into the model's parameters as cost-based accounting is more widely implemented. The tracking of more specific environmental costs would allow for a more accurate reflection of cost parameters in the model. Even if more specific cost data is obtained, it should be remembered that the general purpose of the acquisition pollution prevention system dynamics model is to demonstrate general trends and not provide specific cost numbers for certain types of weapon systems.

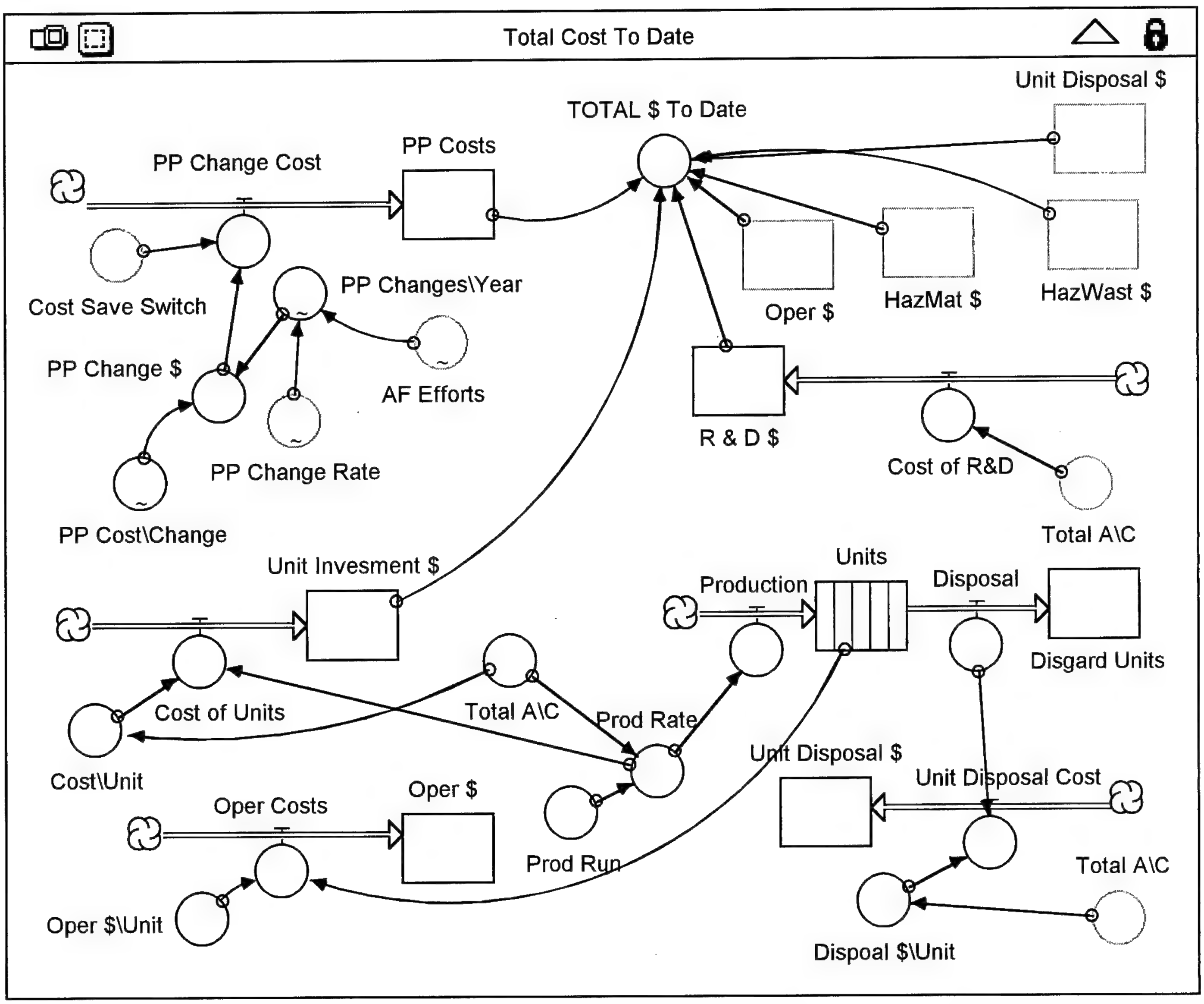
APPENDIX

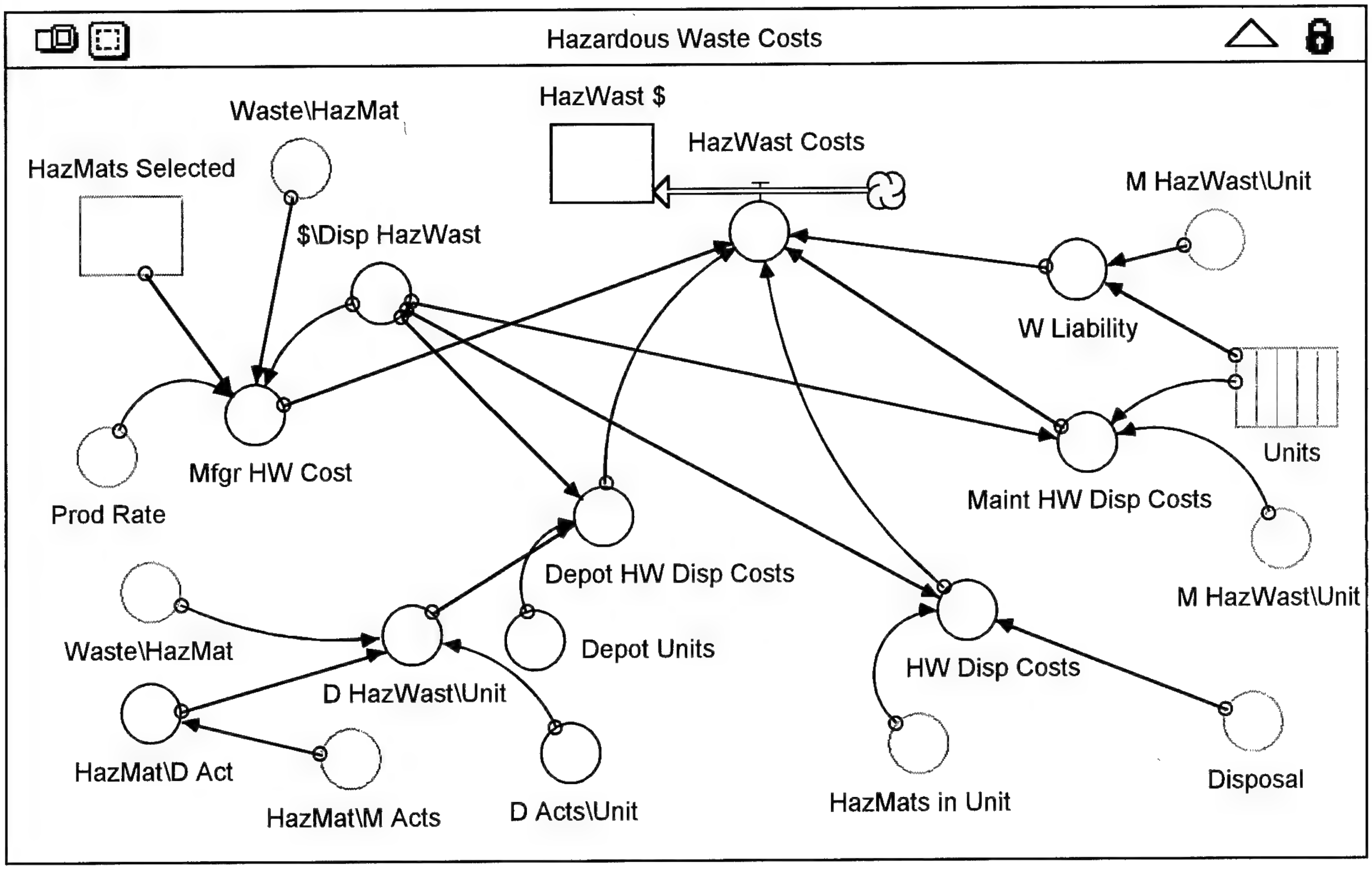

Hazardous Materials Selection
HazMats Selected
HazMats in Unit
HazMat Choice
M HazWast\Unit
HazMats
Cost Save Switch
M HazMats\Unit
HazMat\Yr
ES&H Req
PP Changes\Year
Waste\HazMat
Substitute
Perf Req
Sub Knwldg
HazMat\M Acts
M Acts\Unit
AF Efforts
PP in Sys Eng
Ktr Efforts
AF Labs

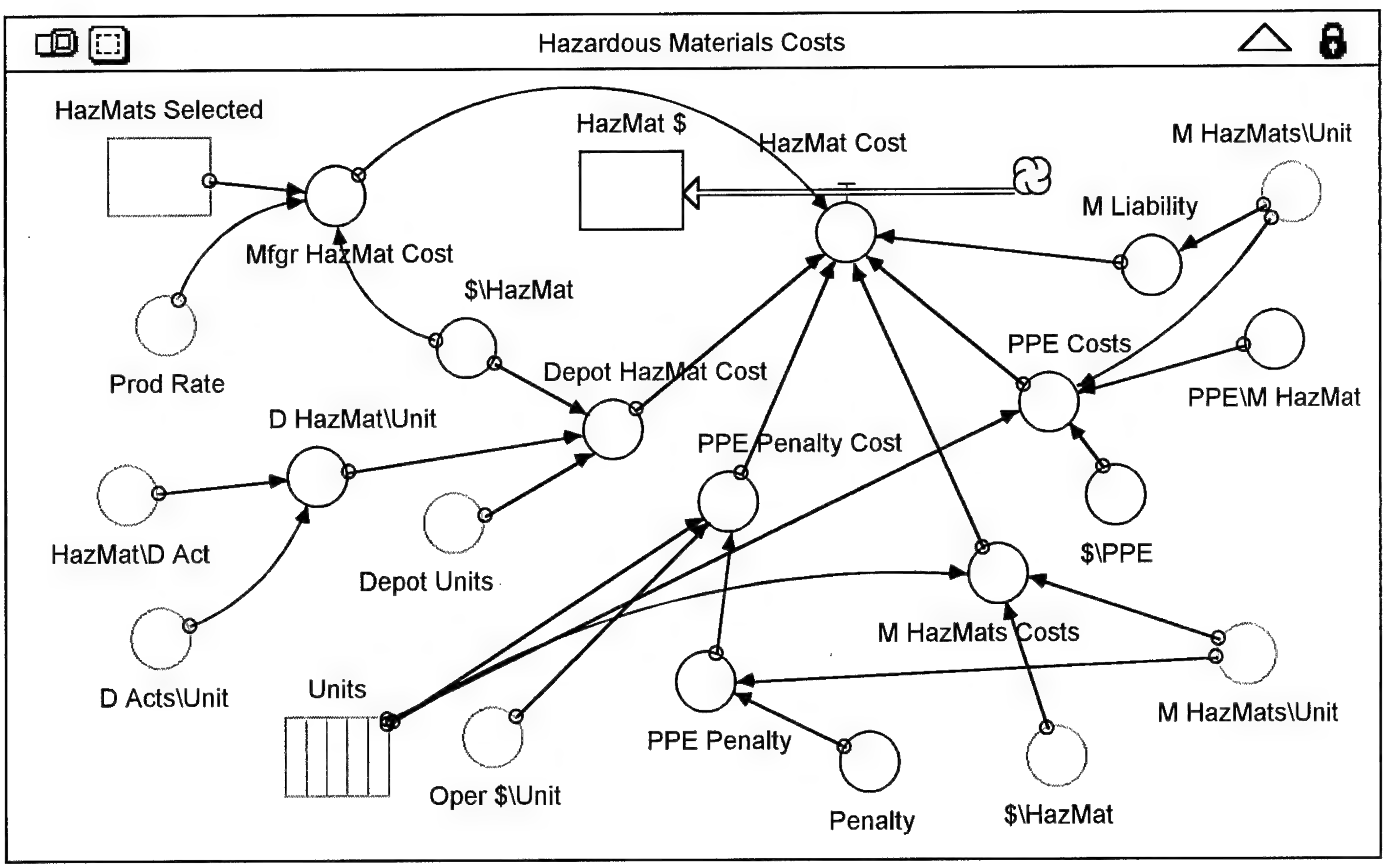

PROJECTED Hazardous Materials and Waste
Prj M HM\Unit
Prj M HW\Unit
Prj HM Selected
Prj HazMat\M Act
Prj HM in Unit
Smoothed
M Acts\Unit
Units
Waste\HazMat
Prj Units
Total A\C
Prj HM Selected
Not Smoothed
Previous Forecast
HazMats Selected
Current Forecast
Prev Forecast
HazMats Selected
Not Smoothed
Smoothed
Alpha

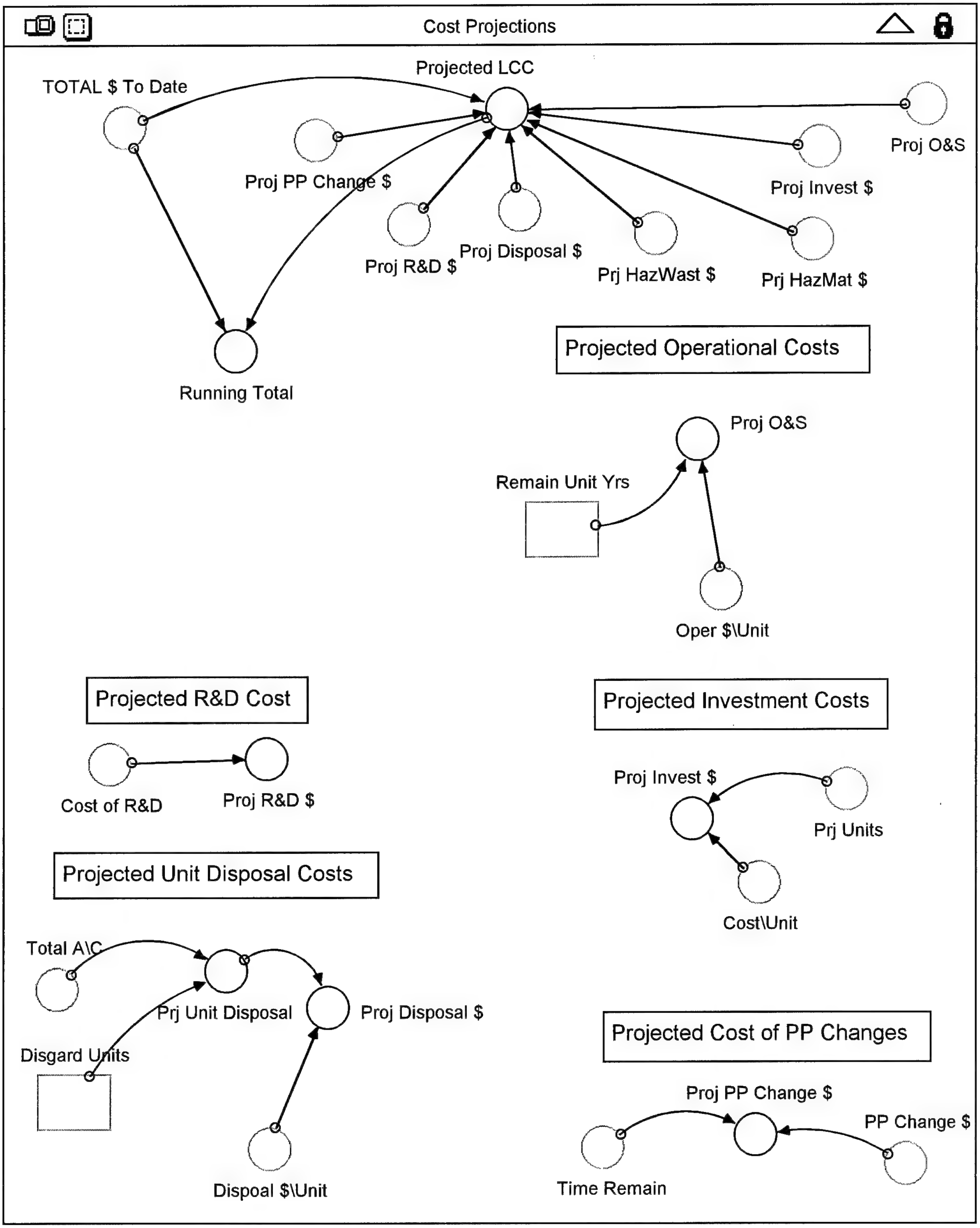

Overall PP On\Off Switch
AF PP On\Off Switch
Pollution Prevention Incentives
Ktr Efforts
AF Efforts
Total AF Effort
Total Ktr Effort
Ktr Effort
PP Change Rate
AF Effort
Ktr Expd Effort
PP in Sys Eng
AF Expd Effort
Cntrct Methods
Reg\Laws
Policy
Cost Driver for PP
AF PP Incent
ES&H Req
AF Labs
Lab Funding
Reg\Law Effc
ES&H Eff
Funding Factor
$ Driver for PP
$ Driver Effc
Policy Effc
Reg\Law Effc
Reg\Laws
Cost Driver for PP
Overshoot Driver for PP
o\o Delta Cost
TOTAL $ To Date
HazMat $
HazWast $
Total A\C
LCC $ Goal
Projected LCC


Cost Savings
Time Remain
System's Life Time
Cost Saved
Discount Rate
Cost Savings?
PP Change $
PP Changes\Year
$ of Each HazMat
Cost Save Switch
Prj HazMat $
Prj HM Selected
Prj HazWast $

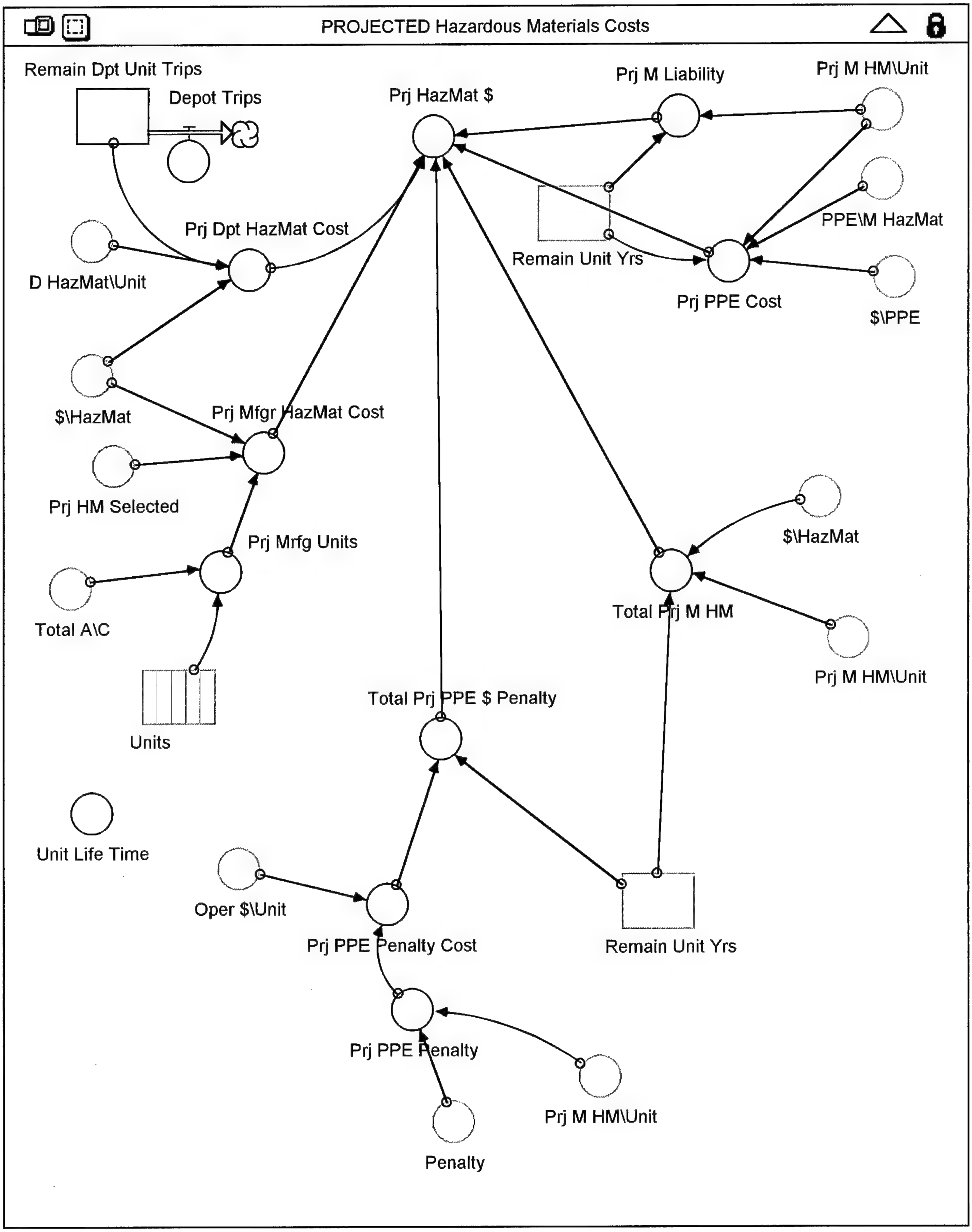

Total Cost To Date
Unit Disposal $
TOTAL $ To Date
PP Costs
PP Change Cost
Cost Save Switch
PP Changes\Year
Oper $
HazMat $
HazWast $
PP Change $
AF Efforts
R & D $
PP Change Rate
Cost of R&D
PP Cost\Change
Total A\C
Unit Invesment $
Units
Production
Disposal
Disgard Units
Cost of Units
Total A\C
Prod Rate
Cost\Unit
Unit Disposal $
Unit Disposal Cost
Oper Costs
Oper $
Prod Run
Total A\C
Oper $\Unit
Dispoal $\Unit

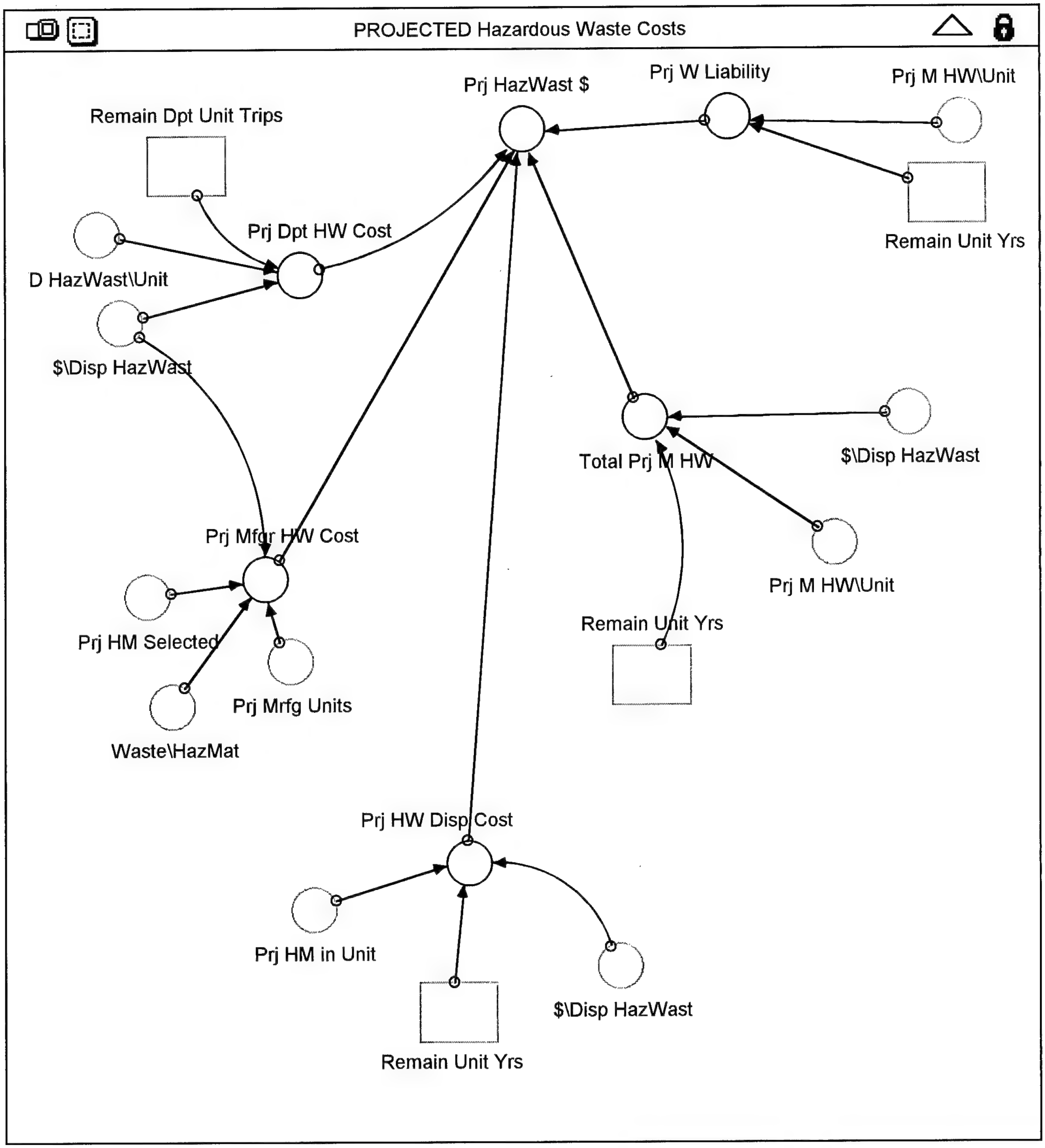

Hazardous Waste Costs
HazWast $
HazWast Costs
Waste\HazMat
HazMats Selected
$\Disp HazWast
M HazWast\Unit
W Liability
Units
Mfgr HW Cost
Prod Rate
Maint HW Disp Costs
Depot HW Disp Costs
M HazWast\Unit
Waste\HazMat
Depot Units
D HazWast\Unit
HW Disp Costs
HazMat\D Act
HazMat\M Acts
D Acts\Unit
HazMats in Unit
Disposal

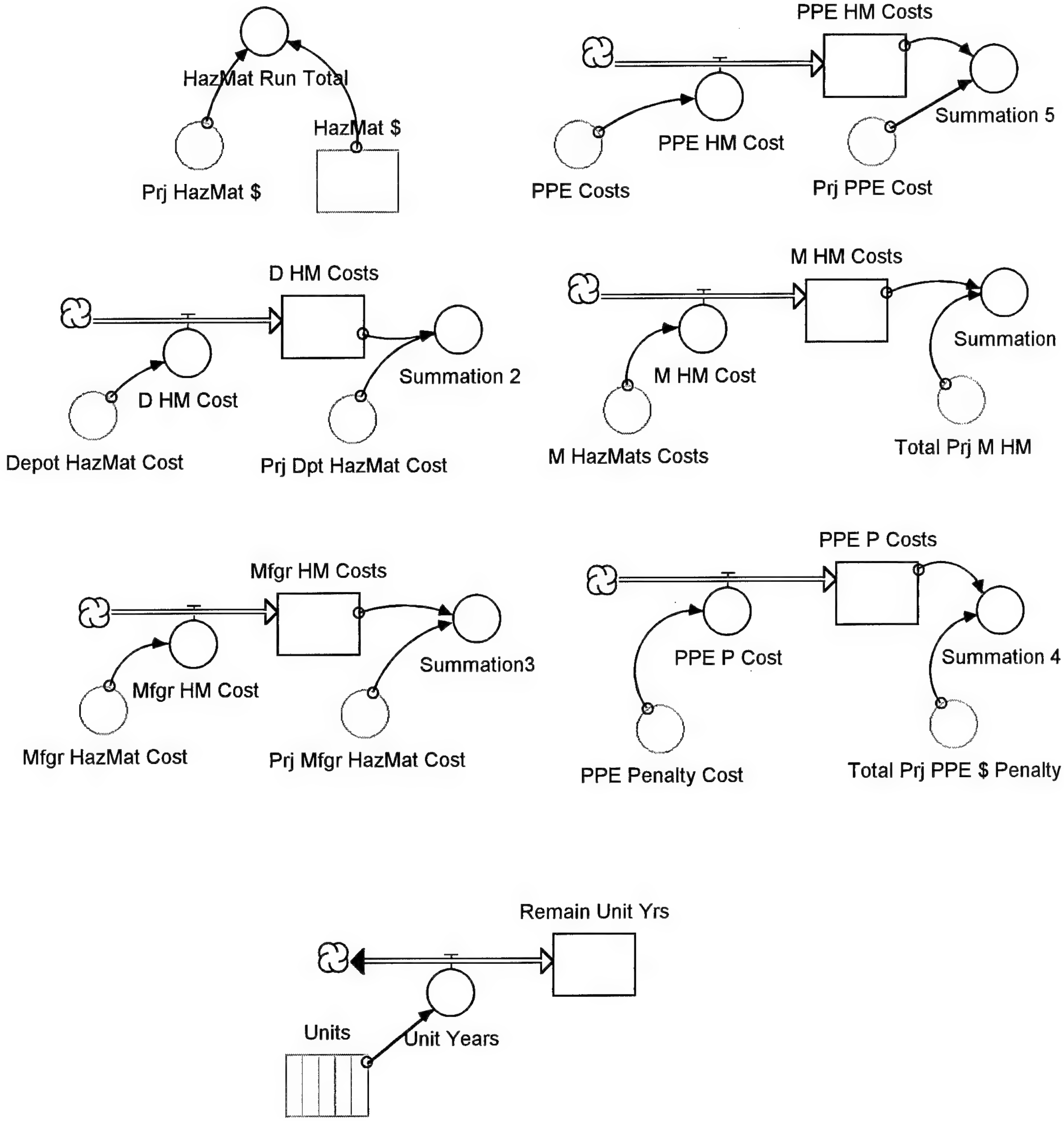

Hazardous Materials Costs
HazMats Selected
HazMat $
HazMat Cost
M HazMats\Unit
M Liability
Mfgr HazMat Cost
$\HazMat
Prod Rate
Depot HazMat Cost
PPE Costs
PPE\M HazMat
D HazMat\Unit
PPE Penalty Cost
HazMat\D Act
Depot Units
$\PPE
M HazMats Costs
D Acts\Unit
Units
M HazMats\Unit
PPE Penalty
Oper $\Unit
Penalty
$\HazMat



Cost Projections
Projected LCC
TOTAL $ To Date
Proj PP Change $
Proj R&D $
Proj Disposal $
Prj HazWast $
Prj HazMat $
Proj Invest $
Proj O&S
Running Total
Projected Operational Costs
Proj O&S
Remain Unit Yrs
Oper $\Unit
Projected R&D Cost
Cost of R&D
Proj R&D $
Projected Investment Costs
Proj Invest $
Prj Units
Cost\Unit
Projected Unit Disposal Costs
Total A\C
Prj Unit Disposal
Proj Disposal $
Disgard Units
Dispoal $\Unit
Projected Cost of PP Changes
Proj PP Change $
PP Change $
Time Remain


PROJECTED Hazardous Materials Costs
Remain Dpt Unit Trips
Depot Trips
Prj HazMat $
Prj M Liability
Prj M HM\Unit
PPE\M HazMat
Remain Unit Yrs
Prj Dpt HazMat Cost
D HazMat\Unit
Prj PPE Cost
$\PPE
$\HazMat
Prj Mfgr HazMat Cost
Prj HM Selected
Prj Mrfg Units
$\HazMat
Total A\C
Total Prj M HM
Prj M HM\Unit
Units
Total Prj PPE $ Penalty
Unit Life Time
Oper $\Unit
Prj PPE Penalty Cost
Remain Unit Yrs
Prj PPE Penalty
Prj M HM\Unit
Penalty


PROJECTED Hazardous Waste Costs
Prj HazWast $
Prj W Liability
Prj M HW\Unit
Remain Dpt Unit Trips
Prj Dpt HW Cost
Remain Unit Yrs
D HazWast\Unit
$\Disp HazWast
Total Prj M HW
$\Disp HazWast
Prj Mfgr HW Cost
Prj M HW\Unit
Remain Unit Yrs
Prj HM Selected
Prj Mrfg Units
Waste\HazMat
Prj HW Disp Cost
Prj HM in Unit
$\Disp HazWast
Remain Unit Yrs


HazMat Run Total
HazMat $
Prj HazMat $
PPE HM Costs
Summation 5
PPE HM Cost
PPE Costs
Prj PPE Cost
D HM Costs
Summation 2
D HM Cost
Depot HazMat Cost
Prj Dpt HazMat Cost
M HM Costs
Summation
M HM Cost
M HazMats Costs
Total Prj M HM
Mfgr HM Costs
Summation3
Mfgr HM Cost
Mfgr HazMat Cost
Prj Mfgr HazMat Cost
PPE P Costs
Summation 4
PPE P Cost
PPE Penalty Cost
Total Prj PPE $ Penalty
Remain Unit Yrs
Units
Unit Years

Cost Projections
Prj_Unit_Disposal = Total_A\C-Disgard_Units
DOCUMENT: The number of units (existing or to be built) remaining for disposal

Projected_LCC = Proj_Disposal_$+Proj_Invest_$+Proj_O&S+Proj_PP_Change_$+ Proj_R&D_$ +Prj_HazMat_$ +Prj_HazWast_$+TOTAL_$_To_Date
DOCUMENT: The total projected "end of the life cycle" cost of the program consisting of all the money spent to-date plus all projected costs

Proj_Disposal_$ = (Dispoal_$\Unit*Prj_Unit_Disposal)

Proj_Invest_$ = Prj_Units*Cost\Unit

Proj_O&S = Remain_Unit_Yrs*Oper_$\Unit
DOCUMENT: Remaining unit year represents the number of units (existing or "to be built") times their remaining life cycles (20 or less). Multiplying by the operational cost per unit per year yields the total remaining (projected) O&S cost.

Proj_PP_Change_$ = IF TIME > 0 THEN (PP_Change_$*Time_Remain) ELSE 0
DOCUMENT: Multiplying the current annual cost for pollution prevention changes times the remaining time of the system's life cyle yields projected change costs for pollution prevention

Proj_R&D_$ = Cost_of_R&D*(10-Time)
DOCUMENT: 10-TIME provides the number of years left in the 10 year R&D program. Multiplying this by the annual cost of R&D yields the projected remaining R&D cost.

Running_Total = Projected_LCC+TOTAL_$_To_Date
DOCUMENT: Converter used during model testing.

Cost Savings
$_of_Each_HazMat = (Prj_HazMat_$+Prj_HazWast_$)/Prj_HM_Selected
DOCUMENT: The total projectd cost of hazardous materials is calculated by summing the projected HazMat and HazWaste cost. Dividing by the number of projected Hazardous Matrials yields the projected cost of each hazadous material per year

Cost_Saved =
(PP_Changes\Year*$_of_Each_HazMat)*(1/(1+Discount_Rate)^Time_Remain)
DOCUMENT: The number of HazMats eliminated each year (Pollution Prevention Changes/Year) times the cost of each HazMat gives the cost that could be saved that year. The net present value of the cost savings is then calculated using the given interest and the time remaining in the programs life cycle.

Cost_Save_Switch = IF Cost_Savings? < 0 THEN 0 ELSE 1

Cost_Savings? = Cost_Saved-PP_Change_$

DOCUMENT: If the cost saved is greater then the cost to implement the PP Change, the Cost Savings switch is set at 1 (on); otherwise, it is set at 0 (off).

Discount_Rate = .06

System's_Life_Time = 40
DOCUMENT: The total projected life span of the system (i.e. years before last unit is retired)

Time_Remain = System's_Life_Time-TIME
DOCUMENT: Time left in the weapon systems life cycle

Hazardous Materials Costs
HazMat_$(t) = HazMat_$(t - dt) + (HazMat_Cost) * dt
INIT HazMat_$ = 0
INFLOWS:
    HazMat_Cost = Depot_HazMat_Cost+Mfgr_HazMat_Cost+PPE_Costs+
    PPE_Penalty_Cost+M_Liability+M_HazMats_Costs

$\HazMat = .0005
DOCUMENT: $500/use/year This is a WAG. It may seem low at first, but it represents the cost everytime a hazardous materials is used (not just to buy a drum of something)

$\PPE = .0005
DOCUMENT: $500/PPE in $M = .0005

Depot_HazMat_Cost = $\HazMat*(D_HazMat\Unit*Depot_Units)

D_HazMat\Unit = D_Acts\Unit*HazMat\D_Act

Mfgr_HazMat_Cost = $\HazMat*(HazMats_Selected*Prod_Rate)
DOCUMENT: HazMat selected per unit manufactured is multiplied by the production rate to yield total # of HazMats/Year in manufacturing. This in-turn is multiplied by the cost per hazardous materials

M_HazMats_Costs = $\HazMat*M_HazMats\Unit*Units

M_Liability = M_HazMats\Unit*(.001)
DOCUMENT: Instead of representing with a finite graph, estimate $1000 liability per hazardous material

Penalty = 1*10^-4
DOCUMENT: Instead of using a finite graph, this factor is used to help generate the overall PPE % $ Penalty tacked onto the O&S costs.

PPE\M_HazMat = .75

DOCUMENT: Represents the fact that PPE can be reused so you do not need an entirely new piece of PPE every time a hazardous material is used

PPE_Costs = $\PPE*M_HazMats\Unit*PPE\M_HazMat*Units

PPE_Penalty = Penalty*M_HazMats\Unit
DOCUMENT: The Penalty factor times the number of Maintenance Hazardous Material/Unit determines the overall PPE % Cost Penalty used. This ties the % Penalty to the actual # of HazMats

PPE_Penalty_Cost = Units*Oper_$\Unit*PPE_Penalty

Hazardous Materials Selection
HazMats_Selected(t) = HazMats_Selected(t - dt) + (HazMat_Choice) * dt
INIT HazMats_Selected = .000001
INFLOWS:

HazMat_Choice = IF TIME < 10 THEN (HazMats*HazMat\Yr)-(PP_Changes\Year*Cost_Save_Switch) ELSE (-PP_Changes\Year*Cost_Save_Switch)

DOCUMENT: If the Cost Savings Switch is on, then during R&D (the first 10 years) the hazardous materials can be selected at the rate ranging from 0-20 per year (depending on the strength of the HazMats influence) and any pollution prevention efforts are subtracted from this rate. After R&D it is assumed no more hazardous materials are added to the system, but the total amount of hazardous materials can still be reduced by PP Changes\Year. If the cost savings switch is off, this PP Changes\year variable is "zeroed-out"

HazMats = IF Perf_Req - MEAN(Substitute,Sub_Knwldg, ES&H_Req) < 0 THEN 0 ELSE Perf_Req - MEAN(Substitute,Sub_Knwldg, ES&H_Req)
DOCUMENT: A soft variable ranging from 0 (no HazMats are selected) to 1 (the maxiumum # of HazMats is selected). Using the MEAN(Substitute,Sub_Knwldg,ES&H_Req) assumes equal weights. These three influences reduce the need to used hazardous materials driven by the performance requirements.

HazMats_in_Unit = HazMats_Selected*(.20)
DOCUMENT: Assumes 20% of the hazardous materials selected for the design actually end up intrinsic to the unit itself.

HazMat\M_Acts = HazMats_Selected*(.25/400)
DOCUMENT: The F-22 has approximately 400 Hazardous Materials and it is estimated that only 30% their maintenance tasks contain hazardous materials. Assuming a linear relationship of y=mx +b with and x/y intercept of 0/0 the Y = .30/400(X) + 0

HazMat\Yr = 300

DOCUMENT: An estimate of the maximum number of hazardous materials that can be chose a year during the design phase

M_Acts\Unit = 1000
DOCUMENT: An WAG based on the fact the F-22 has approximately 7000 maintenance actions in its LSA data base; however, not all the actions are performed on every unit every year.

M_HazMats\Unit = M_Acts\Unit*HazMat\M_Acts

M_HazWast\Unit = Waste\HazMat*M_HazMats\Unit

Perf_Req = .8

Substitute = IF (Ktr_Efforts+AF_Efforts+AF_Labs) <1 THEN (Ktr_Efforts+AF_Efforts+AF_Labs) ELSE 1
DOCUMENT: Either one of these influences by itself would be able to maximize the substitution efforts

Waste\HazMat = .2
DOCUMENT: An estimate of the percent of hazardous materials converted to hazardous waste

Sub_Knwldg = GRAPH(MEAN(Substitute,Ktr_Efforts,PP_in_Sys_Eng))
(0.00, 0.00), (0.1, 0.015), (0.2, 0.03), (0.3, 0.055), (0.4, 0.095), (0.5, 0.185), (0.6, 0.29), (0.7, 0.41), (0.8, 0.575), (0.9, 0.78), (1, 1.00)

Hazardous Waste Costs
HazWast_$(t) = HazWast_$(t - dt) + (HazWast_Costs) * dt
INIT HazWast_$ = 0
INFLOWS:
    HazWast_Costs =
    (Mfgr_HW_Cost)+(Depot_HW_Disp_Costs)+(HW_Disp_Costs)
    +(Maint_HW_Disp_Costs)+(W_Liability)

$\Disp_HazWast = .001
DOCUMENT: $1,000 dollars: This is a WAG. It may seem low at first, but it represents the cost every time a hazardous generated (not just to treat a drum of something)

Depot_HW_Disp_Costs = $\Disp_HazWast*(D_HazWast\Unit*Depot_Units)

Depot_Units = IF TIME <= 15 OR TIME > 35 THEN 0 ELSE (IF TIME <= 30 and TIME >20 THEN 60 ELSE 30)
DOCUMENT: No units are returned to depot for over-haul the first 15 years (no units are produced the first 10 years plus the unit is in the field 5 years before it is returned). Also no units are returned after 35 years (because the are with in 5 years of disposal). Between 20 and 30 years, 60 units/yr are returned to the depot, otherwise only 30/yr.

D_Acts\Unit = 1000
DOCUMENT: An estimate of the number of depot actions per unit base on F-22 data

D_HazWast\Unit = D_Acts\Unit*Waste\HazMat*HazMat\D_Act

HazMat\D_Act = HazMat\M_Acts*(80/20)
DOCUMENT: An estimate of the number of depot actions containing HazMats based compared to the number of maintenance actions containing HazMats (F-22 information shows a 80 M Acts with HazMats vs 20 D Acts with HazMats)

HW_Disp_Costs = $\Disp_HazWast*HazMats_in_Unit*Disposal

Maint_HW_Disp_Costs = M_HazWast\Unit*$\Disp_HazWast*Units

Mfgr_HW_Cost = $\Disp_HazWast*(HazMats_Selected*Waste\HazMat*Prod_Rate)
DOCUMENT: HazMat selected per unit mnfg is converted to HazWaste per unit mnfg This is multiplied by the waste disposal cost to get HazWaste cost per unit. This is then multiplied by the production rate for each year.

W_Liability = Units*M_HazWast\Unit*(.003)
DOCUMENT: Instead of representing with a finite graph, estimate $3000 liablity per hazardous waste

Pollution Prevention Incentives
Total_AF_Effort(t) = Total_AF_Effort(t - dt) + (AF_Effort - AF_Expd_Effort) * dt
INIT Total_AF_Effort = 1
INFLOWS:
    AF_Effort = PP_Change_Rate * PP_in_Sys_Eng * AF_PP_On\Off_Switch
OUTFLOWS:
    AF_Expd_Effort = (1-PP_Change_Rate)*.3

Total_Ktr_Effort(t) = Total_Ktr_Effort(t - dt) + (Ktr_Effort - Ktr_Expd_Effort) * dt
INIT Total_Ktr_Effort = 1
INFLOWS:
    Ktr_Effort = (IF (Reg\Laws*Reg\Law_Effc) +
    (Cntrct_Methods*PP_Change_Rate) < 1 THEN (Reg\Laws*Reg\Law_Effc) +
    (Cntrct_Methods*PP_Change_Rate) ELSE 1)*Overall_PP_On\Off_Switch
OUTFLOWS:
    Ktr_Expd_Effort = (1-PP_Change_Rate)

$_Driver_Effc = .9

$_Driver_for_PP = IF (Cost_Driver_for_PP + Overshoot_Driver_for_PP) < 1 THEN (Cost_Driver_for_PP+Overshoot_Driver_for_PP) ELSE 1

AF_Labs = (IF (Policy_Effc*Policy) + PP_in_Sys_Eng < 1 THEN (Policy*Policy_Effc) + PP_in_Sys_Eng ELSE 1)*Lab_Funding

AF_PP_Incent = (IF ($_Driver_Effc*$_Driver_for_PP) + (Policy_Effc*Policy) + (Reg\Law_Effc*Reg\Laws) < 1 THEN ($_Driver_Effc*$_Driver_for_PP) + (Policy_Effc*Policy) + (Reg\Law_Effc*Reg\Laws) ELSE 1)*AF_PP_On\Off_Switch
DOCUMENT: Adding the effects of the policy, laws, and $ incentives (times their respective efficiencies). Either effect by itself is capable of maximizing Air Force PP incentive to 1

ES&H_Eff = .5

ES&H_Req = (IF (Policy_Effc*Policy) + (Reg\Law_Effc*Reg\Laws) <1 THEN (Policy_Effc*Policy) + (Reg\Law_Effc*Reg\Laws) ELSE 1)*ES&H_Eff

Funding_Factor = .5

Lab_Funding = Funding_Factor*Cost_Driver_for_PP

LCC_$_Goal = Total_A\C*1000
DOCUMENT: The total LCC goal is estimated at $1B ($1000 M) per aircraft. All dollars in model are expressed in $ Millions.

o\o_Delta_Cost = ((Projected_LCC-LCC_$_Goal)/LCC_$_Goal)*100
DOCUMENT: The % difference between the projected LCC and the LCC goal. Multiplying by 100 yields the number "in percent" (i.e. 10% = 10)

Policy = 1
DOCUMENT: Scale from 0-1. (1 is the highest effectiveness) Effectiveness of Air Force policy to drive pollution prevention efforts.

Policy_Effc = .5

Reg\Laws = 1
DOCUMENT: Scale from 0-1. (1 is the highest effectiveness) Effectiveness of regulations and laws to drive pollution prevention efforts.

Reg\Law_Effc = .7

AF_Efforts = GRAPH(Total_AF_Effort)
(0.00, 0.005), (1.00, 0.155), (2.00, 0.415), (3.00, 0.625), (4.00, 0.885), (5.00, 0.945), (6.00, 0.99), (7.00, 0.995), (8.00, 1.00), (9.00, 1.00), (10.0, 1.00)

Cntrct_Methods = GRAPH((IF (AF_PP_Incent + PP_in_Sys_Eng) <1 THEN (AF_PP_Incent+PP_in_Sys_Eng) ELSE 1)*AF_PP_On\Off_Switch)
(0.00, 0.095), (0.1, 0.105), (0.2, 0.155), (0.3, 0.245), (0.4, 0.355), (0.5, 0.54), (0.6, 0.8), (0.7, 0.89), (0.8, 0.95), (0.9, 0.98), (1, 1.00)

Cost_Driver_for_PP = GRAPH((HazWast_$+HazMat_$)/TOTAL_$_To_Date)

(0.00, 0.095), (0.001, 0.095), (0.002, 0.1), (0.003, 0.125), (0.004, 0.15), (0.005, 0.18), (0.006, 0.22), (0.007, 0.335), (0.008, 0.515), (0.009, 0.77), (0.01, 1.00)
DOCUMENT: Scale from 0-1. 1 is the best or highest incentive for PP. Since 10% is considered a high PP cost, $ Incentive for PP will be at it's highest when PP cost approach 10% of total costs. Never reaches zero. Always some incentive to do PP.

Ktr_Efforts = GRAPH(Total_Ktr_Effort)
(0.00, 0.01), (1.00, 0.295), (2.00, 0.445), (3.00, 0.655), (4.00, 0.825), (5.00, 0.885), (6.00, 0.945), (7.00, 1.00), (8.00, 1.00), (9.00, 1.00), (10.0, 0.995)

Overshoot_Driver_for_PP = GRAPH(o\o_Delta_Cost)
(0.00, 0.00), (0.5, 0.095), (1.00, 0.2), (1.50, 0.31), (2.00, 0.405), (2.50, 0.5), (3.00, 0.595), (3.50, 0.685), (4.00, 0.805), (4.50, 0.9), (5.00, 1.00)
DOCUMENT: Converts the % Change in LCC (the % LCC is over the LCC goal) into a 0-1 soft variable of incentive to perform pollution prevention

PP_Change_Rate = GRAPH(TIME)
(0.00, 1.00), (3.33, 0.37), (6.67, 0.15), (10.0, 0.105), (13.3, 0.085), (16.7, 0.075), (20.0, 0.06), (23.3, 0.045), (26.7, 0.035), (30.0, 0.03), (33.3, 0.02), (36.7, 0.005), (40.0, 0.00)
DOCUMENT: Pollution Prevention Change rate is a soft variable that falls from 1 (a high rate of change) to 0 (no changes) by the end of the systems life cycle

PP_in_Sys_Eng = GRAPH(AF_PP_Incent)
(0.00, 0.00), (0.1, 0.29), (0.2, 0.475), (0.3, 0.61), (0.4, 0.76), (0.5, 0.885), (0.6, 0.935), (0.7, 0.965), (0.8, 0.98), (0.9, 0.995), (1, 1.00)

PROJECTED Hazardous Materials and Waste

Previous_Forecast(t) = Previous_Forecast(t - dt) + (Current_Forecast - Prev_Forecast) * dt
INIT Previous_Forecast = 0
  TRANSIT TIME = 1
  INFLOW LIMIT = INF
  CAPACITY = INF
INFLOWS:
    Current_Forecast = Smoothed
OUTFLOWS:
    Prev_Forecast = CONVEYOR OUTFLOW

Alpha = IF TIME <10 THEN .1*TIME ELSE 1
DOCUMENT: The correction factor for the error portion of the exponential smoothing function (Schmenner, 1995:143)

Not_Smoothed = IF TIME > 0 THEN HazMats_Selected + (HazMats_Selected/TIME)*(40-TIME) ELSE 0

Prj_HazMat\M_Act = Prj_HM_Selected*(.30/400)

Prj_HM_in_Unit = Prj_HM_Selected*(.20)

Prj_HM_Selected = Smoothed

Prj_M_HM\Unit = M_Acts\Unit*Prj_HazMat\M_Act

Prj_M_HW\Unit = Waste\HazMat*Prj_M_HM\Unit

Prj_Units = IF TIME < 30 THEN (Total_A\C-Units) ELSE 0
DOCUMENT: How many units there are remaining to be fielded. The IF-THEN statement keeps this number from rising once disposal starts

Smoothed = HazMats_Selected+(1-Alpha)*Prev_Forecast

PROJECTED Hazardous Materials Costs

Remain_Dpt_Unit_Trips(t) = Remain_Dpt_Unit_Trips(t - dt) + (- Depot_Trips) * dt
INIT Remain_Dpt_Unit_Trips = 900

DOCUMENT: The projected number of trips each unit will make to the depot times the total number of aircraft. This projected stock is drained as units actually start returning to the depot.

OUTFLOWS:

Depot_Trips = IF TIME >= 15 and TIME <= 35 THEN (If TIME >= 30 then (30) else if TIME >= 20 then (60) else(30)) ELSE 0

Prj_Dpt_HazMat_Cost = Remain_Dpt_Unit_Trips*$\HazMat*D_HazMat\Unit

Prj_HazMat_$ = Prj_Mfgr_HazMat_Cost + Prj_Dpt_HazMat_Cost + Total_Prj_M_HM+ Prj_M_Liability + Prj_PPE_Cost +Total_Prj_PPE_$_Penalty

Prj_Mfgr_HazMat_Cost = Prj_HM_Selected*$\HazMat*Prj_Mrfg_Units

Prj_Mrfg_Units = IF TIME <30 THEN (IF (Total_A\C-Units) >=0 THEN (Total_A\C-Units) ELSE 0) ELSE 0

Prj_M_Liability = Prj_M_HM\Unit*(.001)*Remain_Unit_Yrs

Prj_PPE_Cost = $\PPE*Prj_M_HM\Unit*PPE\M_HazMat*Remain_Unit_Yrs

Prj_PPE_Penalty = Penalty*Prj_M_HM\Unit

Prj_PPE_Penalty_Cost = IF TIME > 0 THEN (Oper_$\Unit*Prj_PPE_Penalty) ELSE 0

Total_Prj_M_HM = Remain_Unit_Yrs*$\HazMat*Prj_M_HM\Unit

Total_Prj_PPE_$_Penalty = Remain_Unit_Yrs*Prj_PPE_Penalty_Cost

Unit_Life_Time = 20

PROJECTED Hazardous Waste Costs

Prj_Dpt_HW_Cost = Remain_Dpt_Unit_Trips*$\Disp_HazWast*D_HazWast\Unit

Prj_HazWast_$ = Prj_Mfgr_HW_Cost + Prj_Dpt_HW_Cost + Prj_W_Liability +
Prj_HW_Disp_Cost +Total_Prj_M_HW

Prj_HW_Disp_Cost = Prj_HM_in_Unit*$\Disp_HazWast*Remain_Unit_Yrs

Prj_Mfgr_HW_Cost =
Prj_HM_Selected*Prj_Mrfg_Units*Waste\HazMat*$\Disp_HazWast

Prj_W_Liability = Prj_M_HW\Unit*(.003)*Remain_Unit_Yrs

Total_Prj_M_HW = Remain_Unit_Yrs*$\Disp_HazWast*Prj_M_HW\Unit

Total Cost To Date

Disgard_Units(t) = Disgard_Units(t - dt) + (Disposal) * dt
INIT Disgard_Units = 0
INFLOWS:
Disposal = CONVEYOR OUTFLOW

Oper_$(t) = Oper_$(t - dt) + (Oper_Costs) * dt
INIT Oper_$ = 0
INFLOWS:
Oper_Costs = Units*Oper_$\Unit

PP_Costs(t) = PP_Costs(t - dt) + (PP_Change_Cost) * dt
INIT PP_Costs = 0
INFLOWS:
PP_Change_Cost = PP_Change_$*Cost_Save_Switch

R_&_D_$(t) = R_&_D_$(t - dt) + (Cost_of_R&D) * dt
INIT R_&_D_$ = 0
INFLOWS:
Cost_of_R&D = IF TIME < 10 THEN (Total_A\C*1000)*(.10)/10 ELSE 0
DOCUMENT: The total number of aircraft time $1 B (or $1000 M) each is total program cost. Then take 10% of this for R&D costs. Divide this by 10 years (the length of the R & D program) to get an approximate R&D cost per year.

Units(t) = Units(t - dt) + (Production - Disposal) * dt
INIT Units = 0
TRANSIT TIME = 20
INFLOW LIMIT = INF
CAPACITY = INF
INFLOWS:
Production = Prod_Rate
OUTFLOWS:
Disposal = CONVEYOR OUTFLOW

Unit_Disposal_$(t) = Unit_Disposal_$(t - dt) + (Unit_Disposal_Cost) * dt
INIT Unit_Disposal_$ = 0
INFLOWS:
    Unit_Disposal_Cost = Disposal*Dispoal_$\Unit

Unit_Invesment_$(t) = Unit_Invesment_$(t - dt) + (Cost_of_Units) * dt
INIT Unit_Invesment_$ = 0
INFLOWS:
    Cost_of_Units = Cost\Unit*Prod_Rate

Cost\Unit = (Total_A\C*1000)*(.30)/Total_A\C
DOCUMENT: Investment cost is 30% of overall program cost (Aircraft X $1000M). Dividing the investment cost by the total number of aircraft yields a per aircraft investment cost.

Dispoal_$\Unit = (Total_A\C*1000)*(.10)/Total_A\C
DOCUMENT: Disposal cost is 10% of overall program cost (Aircraft X $1000M). Dividing the investment cost by the total number of aircraft yields a per aircraft disposal cost.

Oper_$\Unit = 25
DOCUMENT: From year 20 to 30 there is a constant 300 units in the field. The O&S cost under this part of the curve 1/2 of the total $150 B O&S total cost ($1 B X Total Units X 50% = $150B half = $75B). $75B/300 Units/10 years gives the O&S cost per unit per year of $25M.

PP_Change_$ = PP_Changes\Year*PP_Cost\Change

Prod_Rate = IF TIME >= 10 and TIME < 20 THEN (Total_A\C/Prod_Run) ELSE 0
DOCUMENT: Production rate equals the total number of aircraft desired divided by the number of years required to manufacture them.

Prod_Run = 10
DOCUMENT: The number of years the aircraft will be manufactured.

TOTAL_$_To_Date = HazMat_$+HazWast_$+Oper_$+Unit_Invesment_$+PP_Costs + R_&_D_$+Unit_Disposal_$

Total_A\C = 300

PP_Changes\Year = GRAPH(MEAN (AF_Efforts,PP_Change_Rate))
(0.00, 0.00), (0.1, 0.2), (0.2, 0.35), (0.3, 0.7), (0.4, 1.15), (0.5, 2.00), (0.6, 2.90), (0.7, 4.10), (0.8, 5.45), (0.9, 7.20), (1, 10.0)
DOCUMENT: The number of HazMats that can be eliminated each year. Assumes 10 maximum changes per year if the mean of Air Force Efforts and the PP Change Rate = 1.0 (its maximum value)

PP_Cost\Change = GRAPH(TIME)
(0.00, 0.2), (3.33, 0.25), (6.67, 0.5), (10.0, 0.7), (13.3, 0.85), (16.7, 1.18), (20.0, 1.33), (23.3, 1.58), (26.7, 2.05), (30.0, 2.35), (33.3, 2.90), (36.7, 4.20), (40.0, 4.98)

Not in a sector
D_HM_Costs(t) = D_HM_Costs(t - dt) + (D_HM_Cost) * dt
INIT D_HM_Costs = 0

INFLOWS:
D_HM_Cost = Depot_HazMat_Cost
Mfgr_HM_Costs(t) = Mfgr_HM_Costs(t - dt) + (Mfgr_HM_Cost) * dt
INIT Mfgr_HM_Costs = 0

INFLOWS:
Mfgr_HM_Cost = Mfgr_HazMat_Cost
M_HM_Costs(t) = M_HM_Costs(t - dt) + (M_HM_Cost) * dt
INIT M_HM_Costs = 0

INFLOWS:
M_HM_Cost = M_HazMats_Costs
PPE_HM_Costs(t) = PPE_HM_Costs(t - dt) + (PPE_HM_Cost) * dt
INIT PPE_HM_Costs = 0
INFLOWS:
PPE_HM_Cost = PPE_Costs

PPE_P_Costs(t) = PPE_P_Costs(t - dt) + (PPE_P_Cost) * dt
INIT PPE_P_Costs = 0
INFLOWS:
PPE_P_Cost = PPE_Penalty_Cost

Remain_Unit_Yrs(t) = Remain_Unit_Yrs(t - dt) + (Unit_Years) * dt
INIT Remain_Unit_Yrs = 6000
INFLOWS:
Unit_Years = -Units

AF_PP_On\Off_Switch = 1*Overall_PP_On\Off_Switch

HazMat_Run_Total = HazMat_$ + Prj_HazMat_$

Overall_PP_On\Off_Switch = 1

Summation = M_HM_Costs+Total_Prj_M_HM
Summation3 = Mfgr_HM_Costs+Prj_Mfgr_HazMat_Cost
Summation_2 = D_HM_Costs+Prj_Dpt_HazMat_Cost
Summation_4 = PPE_P_Costs+Total_Prj_PPE_$_Penalty
Summation_5 = PPE_HM_Costs+Prj_PPE_Cost

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Vita

Mr. Tedmond B. Grady was born on 28 March 1962 in Detroit, Michigan. He graduated from Vandalia Butler High School in Vandalia, Ohio, in 1980. He earned a Bachelor of Science degree in Chemical Engineering from Ohio University at Athens, Ohio, in 1984.

Mr. Grady began his DoD civilian career as a system safety engineer in July 1985 in the Aeronautical System Center (ASC), System Safety Directorate, at Wright-Patterson Air Force Base, Ohio. He performed duties as a system safety engineer in the Strategic Systems System Program Office, and as Chief of System Safety, which included environmental responsibilities, for the Advanced Cruise Missile Program. In 1989, Mr. Grady changed AFSCs to environmental engineering and was instrumental in establishing the pollution prevention program for the F-22, one of the Air Force's first acquisition pollution prevention programs. In June 1996, he left his position as the senior environmental advisor for the ASC Aircraft Product Support Office to enter the Graduate School of Engineering, Air Force Institute of Technology (AFIT). Mr. Grady will return to the ASC Environmental Directorate upon completion of his maters degree program at AFIT.

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13. ABSTRACT *(Maximum 200 words)*

This research develops a system structure for the pollution prevention acquisition process and uses system dynamics modeling to develop management strategies that optimize life cycle cost. The structure of the pollution prevention acquisition process is developed by identifying primary influences and mechanisms and determining how they interact within the acquisition process. The model structure is based on the premise that rising total projected Life Cycle Cost (LCC) would provide an incentive to perform pollution prevention changes to reduce the overall LCC cost. The model successfully produces the expected reasonable behavior and confidence in the model structure is achieved using standard system dynamics verification testing.

In the model, laws and regulations appear to have the greatest impact on reducing overall LCC; however, this is driven by the high effectiveness values assigned in the model, which assume the ability of laws and regulations to directly address material substitution in the specified weapon system. Air Force Policies and financial incentives (the projected LCC exceeding the LCC goal) also have significant effects on reducing overall LCC. Further defining these parameters to accurately affect the appropriate degree of influence in the model structure is an integral part of developing an effective pollution prevention management strategy.

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